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Investigating the role of oscillations in endogenous and exogenous attentional states: novel methods in neurophenomenology

Étude du rôle des oscillations dans les états attentionnels endogènes et exogènes : les nouvelles méthodes en neurophénoménologie

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It is paradoxical, yet true, to say, that the more we know, the more ignorant we become in the absolute sense, for it is only through enlightenment that we become conscious of our limitations. Precisely one of the most gratifying results of intellectual evolution is the continuous opening up of new and greater prospects.

~ Nikola Tesla

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Abstract

The work presented in this thesis aims to extend our scientific understanding of the subtle relationships between our phenomenological experience of specific states of consciousness, and the corresponding and potentially causal effects on neural activity. In our first experiment, we focused on a phenomenon referred to as spontaneous thought or mind wandering. Our vastly complex inner landscape is an essential aspect of our conscious experience, with research suggesting that people are engaged in some form of inner dialogue unrelated to their surroundings 50% of waking hours. These ongoing trains of thought have been consistently linked to reports of negative affect, even when the specific content is positive. Interestingly, the cornerstones of most meditation and contemplative practices are; a) training the continuous and flexible monitoring of mind wandering and sensory experience, b) the cultivation of sustained attention, and c) enhanced metacognitive awareness. Given that we are generally unaware of mind wandering when it occurs, meditation practitioners may provide more accurate first person phenomenological reports and descriptions of these temporally fluctuating states given their respective training. Thus, we designed a novel paradigm based on experience sampling probe presentations to gain insight into the dynamic measures of mental activity and EEG during meditation. Our findings suggest that meditation expertise is associated with an attenuated frequency of mind wandering, and that meditation training reduces the susceptibility of the mind to wander subsequently leading to longer periods of reported meditative absorption. Increases in theta activity (4-7 Hz) over frontal midline regions of the cortex, and alpha activity (9-12 Hz) primarily focused over the somatosensory cortex, appear to be markers of sustained meditative states when compared to mind wandering. Based on the robustness of the frontal midline theta in advanced meditators, alongside a multitude of findings demonstrating that frontal theta may serve as the backbone for cognitive control via long range information integration in neural networks throughout the brain, we then developed a methodologically novel and exhaustive neurofeedback protocol with the aim of training frontal midline theta (3.5-6.5 Hz at electrode site Fz) by means of instructing our subjects to engage in focused breathing and other techniques similar to meditation. After eight training sessions, we found that subjects who received real neurofeedback were able to significantly modulate and increase theta activity (3-7 Hz) over frontal regions, whereas subject's receiving age and gender matched sham (pseudo) feedback were not. We additionally observed significant modulations in both the alpha (9-11 Hz) and beta bands (13-20 Hz) in subjects who received real neurofeedback training. Together, these findings provide evidence that we can successfully connect neurophysiological features and data to the phenomenological nature of our subjective experience.

Résumé

Le travail présenté dans cette thèse vise à nous amener à une meilleure compréhension des relations fines entre ce que nous expérimentons phénoménologiquement sous la forme d'états mentaux, et les effets sous-jacents et potentiellement causaux sur l'activité neuronale. Afin d'étendre notre compréhension scientifique de l'expérience consciente, nous avons d'abord mis l'accent sur un phénomène appelé la pensée spontanée ou vagabondage de l'esprit. Notre paysage intérieur est un aspect essentiel et complexe de notre expérience humaine, avec des recherches suggérant que les gens sont engagés dans une forme de dialogue intérieur sans rapport avec leur environnement immédiat 50% de leur temps de veille. De plus, le vagabondage de l'esprit a constamment été associé à un affect négatif, même lorsque son contenu est positif. Il est alors intéressant de noter que les fondements de la plupart des pratiques méditatives et contemplatives sont la formation de l'observation flexible et continue des états mentaux et de l'expérience sensorielle, le développement d'une attention soutenue et la culture de la conscience métacognitive. Étant donné que nous ne sommes généralement pas au courant de la fluctuation temporelle de ces états mentaux dans le temps (vagabondage de l'esprit), les méditants sont des sujets idéaux pour obtenir de manière précise des rapports phénoménologiques et des descriptions des états à la première personne. Ainsi, nous avons conçu un paradigme nouveau basé sur présentation de sondage d'expérience aux méditants afin de mieux comprendre les mesures dynamiques de l'EEG (Electroencéphalographie) pendant la méditation. Nos résultats suggèrent que la pratique experte de méditation est associée à une fréquence atténuée de la pensée spontanée et que l'entraînement à la méditation réduit par la suite la susceptibilité de l'esprit à errer, menant à des périodes d'absorption méditative rapportées comme étant plus longues. Les augmentations de l'activité thêta (4-7 Hz) sur les régions thêta frontales médianes ainsi que l'activité alpha (9-12 Hz), principalement focalisée sur le cortex somatosensoriel, semblent être des marqueurs d'états méditatifs soutenus par rapport au vagabondage mental. Sur la base de la robustesse de l'activité thêta de la ligne médiane frontale chez les méditants avancés, ainsi qu'une multitude de résultats démontrant que l'activité thêta frontale serait le pilier du contrôle cognitif via l'intégration et l'échange d'informations de longue portée, nous avons développé un protocole de neurofeedback méthodologiquement nouveau et exhaustif dans le but d'entraîner l'activité thêta (3.5-6.5 Hz) de la ligne médiane frontale Fz, en donnant comme instruction à nos sujets de s'engager dans des techniques de respiration et de relaxation similaires à la méditation. Nous avons constaté que les sujets qui ont reçu le vrai neurofeedback ont été capables de moduler significativement leur activité thêta Fz (3-7 Hz) à travers huit séances de neurofeedback par rapport aux sujets contrôles qui ont reçu un feedback apparié. Nous avons également observé des modulations significatives dans les bandes de fréquences alpha (9-11 Hz) et bêta (13-20 Hz) chez les sujets qui ont reçu l'entraînement réel de neurofeedback, ainsi que des améliorations sur plusieurs mesures des fonctions exécutives. Nos résultats réduisent davantage l'écart explicatif en reliant caractéristique neurophysiologique et données à la nature phénoménologique de notre experience.

Résumé substantiel français

Suite à l'avènement de méthodes avancées dans le domaine des techniques de neuroimagerie au cours des deux dernières décennies, notre capacité à analyser l'activité neurale avec haute précision temporelle s'est largement accrue, entrainant alors un renouveau de l'intérêt neuroscientifique envers l'espace intérieur de la conscience humaine. Nous avons ainsi assisté à une explosion de recherches scientifiques visant à identifier, reconstruire, déconstruire, qualifier et quantifier les différents états de conscience. On pourrait argumenter cependant que le seul instrument que l'humanité n'ait jamais possédé pour observer véritablement la conscience est la conscience elle-même. Selon les anciennes traditions contemplatives orientales, la capacité d'observation est l'instrument à affiner pour comprendre et observer les subtilités et les origines de l'expérience consciente (Wallace, 2005). La recherche suggère que la conscience humaine est particulièrement propice aux divagations attentionnelles (~ 50% des heures d'éveil, Killingworth et Gilbert, 2011), donc si la conscience doit être utilisée comme instrument d'exploration et d'expérimentation avec elle-même, cette tendance doit être remplacée par la stabilité attentionnelle et la vivacité (Wallace, 1999). Bien qu'un dialogue interne élaboré soit fondamental à notre expérience consciente, ce récit continu peut surgir à des moments inopportuns (Smallwood et al., 2003 ; Schooler et al., 2006). De manière intéressante, les fondements de la plupart des pratiques méditatives et contemplatives consistent à : a) entrainer la prise de conscience des pensées et de l'expérience sensorielle en cours, b) développer une culture de l'attention soutenue, et c) accroitre la sensibilisation métacognitive. Étant donné que nous ne sommes ni conscients des divagations attentionnelles lorsqu'elles se produisent ni des défis méthodologiques que cela représente, les méditants peuvent nous aider à décrire la phénoménologie de ces états temporellement fluctuant.

Sur la base de ces observations, nous avons conçu un nouveau paradigme pour mieux comprendre les mesures dynamiques de l'activité cognitive et neurale au cours de la méditation. L'étude a été menée à l'Institut de recherche de méditation (IRM) à Rishikesh, en Inde. Vingt-

quatre pratiquants de la tradition Himalayenne de méditation Yoga ont participé à cette étude et ont été répartis en deux groupes selon le nombre d'heures d'entrainement accumulées pour ce type de méditation. Les praticiens ayant effectué plus de 3 000 heures de méditation dans le passé étaient considérés comme étant des praticiens experts tandis que ceux qui avaient déclaré avoir pratiqué cette même technique de méditation pendant moins de 1000 heures, et ce de manière irrégulière, ont constitué le groupe de participants considérés comme étant non experts. Les participants ont été invités à méditer sans interruption tout au long de l'expérience dans leur position de méditation standard (soit assis sur le sol, soit assis sur une chaise). Pendant que les participants méditaient été présentées des sondes d'échantillonnage de leur expérience (des questions préenregistrées) à des intervalles aléatoires allant de 30 secondes à 90 secondes tout au long de l'expérience. Chacune de ces sondes se composait de trois questions, toujours présentées dans le même ordre, soit: Q1; « Quel est la profondeur de votre méditation ? » Q2; « Quel est votre niveau de divagation attentionnelle ? » Q3; « Quel est votre niveau de fatigue ? » Chaque participant répondait selon une échelle allant de 0 à 3 (Q1: 0 = méditation superficielle, 3 = état méditatif profond ; Q2: 0 = pas de divagation attentionnelle, 3 = divagation attentionnelle profonde) à l'aide d'un clavier reposant sur ses genoux. Les données d'EEG étaient enregistrées à l'aide d'un système Biosemi à 64 canaux avec un montage 10-20.

Nos résultats comportementaux montrent que la pratique experte de la méditation est associée non seulement à une fréquence atténuée de divagation attentionnelle, à une plus faible profondeur de divagation attentionnelle, mais aussi à une absorption méditative beaucoup plus profonde que celle des participants non-experts. Ces résultats suggèrent que la formation à la méditation peut soit réduire la fréquence des divagations attentionnelles, conduisant par la suite à de plus longues périodes d'absorption méditative, soit d'accroître la conscience métacognitive des individus lorsque leur esprit vagabonde – nous proposons que de futures recherches devraient se concentrer sur la désambiguïsation de ces mécanismes. Nos résultats EEG montrent que l'absorption méditative chez nos participants experts est associée à une augmentation de l'activité thêta (4-7 Hz) sur les régions frontales médianes et une augmentation de l'activité alpha de manière distribuée (9-12 Hz) (avec une significativité accrue sur les zones somatosensorielles). Ces résultats indiquent que l'augmentation de l'activité thêta sur les régions frontales moyennes et de l'activité alpha principalement centrée sur le cortex somatosensoriel sont des marqueurs d'états de conscience d'attention soutenue, renforcés par la pratique de méditation à long terme dans la tradition himalayenne. Outre l'interprétation des oscillations thêta et alpha comme marqueurs de fonctions exécutives dans des tâches à forte demande attentionnelle, des expériences publiées dans la littérature suggèrent que la formation à la méditation peut moduler certains des mécanismes neuronaux impliqués dans le contrôle cognitif et l'attention. Cela suggère une relation fonctionnelle possible entre les sources contribuant à l'activité thêta observée dans les régions frontales et le réseau de contrôle frontopariétal plus large impliqué dans le maintien de représentations des états d'objectif, d'apprentissage et d'attention dirigée (Cavanagh et Frank, 2014; deBettencourt, Cohen , Lee, Norman, et Turk-Browne, 2015). Les rythmes thêta et alpha latéraux moyens observés pendant l'absorption méditative fournissent des preuves directes pour étayer l'hypothèse selon laquelle le maintien des orientations interne et externe de focalisation peut être maintenu par des mécanismes neuraux similaires (Spreng et al 2012). Enfin, les données comportementales et d'EEG dans notre groupe de praticiens experts témoignent d'une meilleure précision métacognitive qui serait possible suite à une pratique de méditation à long terme. Des résultats antérieurs suggèrent que les oscillations corticales peuvent être formées et amplifiées par le contrôle volontaire via des moyens tels que la méditation. L'intérêt croissant pour les oscillations neuronales résulte de la découverte des capacités intrinsèques des réseaux de neurones à résonner et à osciller à des fréquences multiples (Buzsáki, 2004; Hutcheon & Yarom, 2000). Cela suggère que le traitement de l'information pourrait être intégré à plusieurs échelles temporelles et spatiales et qu'une hiérarchie d'oscillations interagirait pour réguler l'intégration sensorielle et l'attention focalisée (Canolty et Knight, 2010; Fries, 2005, Lakatos et al., 2005; Palva, Linkenkaer-Hansen, Näätänen, & Palva, 2005). Il a été suggéré que la taille donnée d'un réseau cérébral fonctionnel pourrait déterminer sa fréquence oscillatoire, et que plus le réseau serait vaste et distribué, plus l'oscillation sous-jacente serait lente (von Stein & Sarnthein, 2000). Des études suggèrent que les oscillations réguleraient la communication à l'intérieur du cerveau par la cohérence (Bastos, Vezoli et Fries, 2015, Canolty et al., 2006) et contribueraient ainsi à la formation de la mémoire (Rutishauser, Ross, Mamelak et Schuman, 2010) et au contrôle cognitif (Mishra & Gazzaley, 2015). Il a été par exemple proposé que l'activité thêta frontale pourrait servir d'épine dorsale pour le contrôle cognitif via l'intégration à longue distance de l'information dans les réseaux neuronaux (Cohen, 2014, Cavanagh & Frank, 2014). Il est admit que le contrôle cognitif permet de planifier et de contrôler des comportements et des pensées complexes (Baumeister, 2002) et que la perturbation de ce réseau est associée à diverses déficiences comportementales et neurocognitives (Goldberg et Seidman, 1991).

Les progrès récents dans le secteur technologique et les connaissances neuroscientifiques sur la nature des oscillations corticales ont donné lieu au Neurofeedback, c'est-à-dire la capacité à contrôler volontairement et à interagir avec sa propre activité neurale lorsqu'un *feedback* (retour) sensoriel est présenté en temps réel. Les résultats de la recherche par deCharms et collègues (2005) suggèrent que le *feedback* sensoriel est crucial pour l'entrainement de l'autorégulation, montrant que les sujets ont la capacité de réduire leur douleur perçue lorsqu'une représentation visuelle de leur activité neurale leur était présentée. Le Neurofeedback est une méthode qui est basée sur des modulations d'activité neurale continue et peut être utilisée pour moduler les oscillations corticales (Enriquez-Geppert, Huster, Scharfenort, et al., 2013, Enriquez- Geppert, Huster, & Herrmann, 2013). Pendant une session de neurofeedback, les participants s'engagent activement dans un *feedback* en temps réel de leur activité neuronale dans une bande de fréquence donnée dans le but de l'influencer de façon volontaire. Le neurofeedback est un système en boucle fermée qui repose sur le principe de conditionnement opérant. Compte tenu de l'intérêt croissant pour le neurofeedback, de son faible coût et du vaste champ d'applications de l'autorégulation neurale dans la restauration et l'amélioration des fonctions cognitives dans des contextes publiques et cliniques, des études scientifiques approfondies et des protocoles scientifiques de validation sont devenu critiques.

Sur la base des résultats de notre première expérience dans laquelle nous avons observé une fréquence réduite des divagations attentionnelles liée à la présence d'oscillations thêta dans les aires frontales moyennes durant l'absorption méditative, nous avons cherché à fermer la boucle causale en développant un protocole neurofeedback ayant pour but d'entrainer cette activité thêta frontale médiane (3-7 Hz au site d'électrode Fz). Nous avons demandé à nos sujets de se concentrer sur leur respiration et d'utiliser des techniques de comptage mental qui ressemblent à la méditation. Nous nous sommes ensuite intéressés aux effets de ce protocole d'entrainement sur la performance comportementale lors de tâches de contrôle cognitif. Douze participants ont reçu un entrainement de neurofeedback réel et douze participants ont reçu un entrainement simulé au cours de huit séances d'entrainement sur deux semaines consécutives. Les séances d'entrainement neurofeedback ont eu lieu du mardi au vendredi dans la première semaine et du lundi au jeudi dans la deuxième semaine. Le premier mardi et le dernier jeudi ont également été consacrés à la collecte des données pour les taches de contrôle cognitif (fonctionnement exécutif – FE d'environ 40 min), avant et après la formation de neurofeedback. Chaque séance d'entraînement de neurofeedback consistait en six blocs d'entraînement de cinq minutes avec des courtes pauses de deux à trois minutes entre chaque bloc. Les pauses de deux minutes entre blocs d'entraînement ont été utilisées pour encourager l'application continue de stratégies et prévenir les baisses de concentration mais également pour que les participants puissent rendre compte des stratégies mises en œuvre au cours du bloc précédent. Toutes les séances de neurofeedback ont été enregistrées à la même heure de la journée pour chaque sujet.

Nos résultats suggèrent que, dans le cadre de notre protocole de neurofeedback, les stratégies de méditation que nous avons suggérées aux participants étaient efficaces pour moduler en temps réel l'activité thêta dans les aires frontales moyennes. Cela n'était pas le cas pour les participants contrôles appareillés en sexe et en âge recevant le neurofeedback simulé. Nous avons également observé des modulations significatives dans les bandes de fréquence alpha (9-11 Hz) et bêta (13-20 Hz) chez les sujets ayant reçu l'entraînement de neurofeedback, ainsi que des temps de réaction significativement plus rapides sur les essais corrects de la tâche de mémoire de travail « N-Back ». À notre connaissance, notre étude est la première à tester la faisabilité de l'entrainement neurofeedback basé sur la mise en œuvre de stratégies de méditation, et à utiliser spécifiquement une bande de fréquence et un emplacement basés sur les résultats de méditants experts. Bien que cette méthode de neurofeedback puisse être considérée comme difficile pour les individus sans aucune expérience de méditation, des résultats antérieurs ont montré que l'autorégulation peut être accomplie pendant le neurofeedback sans que les sujets aient des stratégies hautement cognitives ou explicites, comme en témoigne la recherche sur l'apprentissage associatif et le conditionnement opérant chez les primates et les rongeurs

(Koralek, Jin, Long Ii, Costa, & Carmena, 2012; Fetz, 1969). Ces résultats fournissent la preuve que nous pouvons relier les caractéristiques et les données neurophysiologiques à la nature phénoménologique de notre expérience subjective grâce au neurofeedback. Egalement, ces résultats contribuent à notre compréhension de certaines des relations subtiles entre l'expérience phénoménologique et les effets correspondants au niveau de l’activité cérébrale. Ensemble ces deux études complémentaires effectuées pendant ma thèse ferment la boucle causale en corrélant dans un premier temps une activité neuronale avec un état mental (la méditation), puis en prouvant dans un second temps ces résultats via l’entrainement des sujets à produire cette activité neuronale et l’observation des changements comportementaux liés à cet entrainement.

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Part I

Chapter 1: The dawn of a new era in consciousness studies

1.1 The renaissance of consciousness research

For as long as humans have been able to conceptually grasp the notion of consciousness, they have sought to understand its phenomenological origins. Any attempt to find a widely accepted definition of consciousness leads one amidst a dizzying debate spanning a multitude of philosophical and scientific domains. While scientific research investigating the origins of consciousness has recently gained interest by many prominent neuroscientists, from the advent of cognitive science in the 1950s and 60s and in the years leading up to the 1980's, it was the general view of most cognitive and neuroscientific researchers that the study of behavior and cognition could essentially progress without any explicit account of consciousness. The phobia surrounding the study of consciousness amongst researchers of the 20th century (and still many today) is particularly notable given that up until the early 1900's, the study of consciousness was one of the most fundamental topics of research for essentially every philosopher and psychologist throughout documented history, including Plato, Aristotle, Kant, James, Loke, Descartes, Schopenhauer and Spinoza to name a few. However, upon the arrival of behaviorism and John Watson, the scientific study of consciousness was lay to rest for the majority of the 20th century. The prominent philosopher Daniel Dennett summed up the scientific efforts to unveil the origins of consciousness this way: "Consciousness appears to be the last bastion of occult properties, epiphenomena, immeasurable subjective states – in short, the one area of mind best left to the philosophers. Let them make fools of themselves trying to corral the quicksilver of 'phenomenology' into a respectable theory" (Dennett, 1978, p.149).

Around 20 years ago, this all began to change when scientists and philosophers such as Francis Crick, Christoph Koch and Roger Penrose decided to delve back into the scientific study of consciousness. With the advent of advanced methods in neuroimaging techniques that have facilitated the ability to watch neural activity with relative precision, the neuroscientific interest in the inner landscape of the human mind was revived. Since then we have witnessed an explosion of research aiming to quantify, qualify, deconstruct and reconstruct consciousness into its most fundamental elements. One way of describing consciousness is that there is a qualia or 'sense' of an experience — the subjective, phenomenal 'what it is like' to see a sunrise, hear a wind chime, think about your family, or to fall in love (Dennett, 1978). While this description accounts for the broader experience of what it is like to be conscious, the developing terminology for various states, levels and types of consciousness has expanded the current narrative into a far more nuanced and complex scientific landscape. Take for example, some of the proliferate terminology seen in many publications today: access consciousness, background consciousness, reflexive and pre-reflexive consciousness, phenomenal consciousness, self-consciousness, creature consciousness, state consciousness, monitoring consciousness, fringe consciousness, focal consciousness, peripheral consciousness, conscious awareness, qualia, transparency, consciousness as higher order thought, higher order experience, displaced perception, and so forth (Block, 1995).

1.2 The explanatory gap and the hard problem of consciousness

We all have a very personal and direct experience of what it means to be conscious. While these experiences are at the heart of what make our lives so full of meaning, neuroscientists have yet to discover exactly what gives rise to this direct experience. The simple fact that consciousness remains a mystery to modern science is in many ways a sort of glaring paradox. We have witnessed extraordinary scientific breakthroughs over the last century; traversing through our galaxy, landing on comets and planets, the discovery of quantum mechanics, and according to many we have modeled the science behind the origins of the universe itself. Yet, no one can definitively explain why we are conscious, let alone define it or tell us where it comes from.

For discursive purposes, consciousness can loosely be considered to be "what it is like" to have an experience (Nagel, 1974) and according to David Chalmers, the scientific problem therein lies on the distinguishing between objectivity and subjectivity: the experience of green is essentially a state that is subjective. However according to our current scientific models of neural activity, brain states are considered to be objective and measurable. How can subjective states be objective states? Furthermore, how can a subjective state have a foundation within an objective state? Thus, the problem of closing this explanatory gap has been coined by Chalmers as the 'Hard problem of Consciousness' (Chalmers, 1996) which argues that, given the fundamentally 'subjective' nature of consciousness itself, there can never truly be an 'objective' science of consciousness.

Thus far, the centerpiece of the scientific study of consciousness has been the search for the neural correlates of consciousness (NCC). Enormous progress has been made in the last few decades regarding the correlations between specific activity in certain regions of the brain and certain aspects of experience (G. Tononi & Koch, 2008). This work has been answering questions about what specific areas of the brain correlate with specific types of behavior and experience. These are however, according to Chalmers, addressing the 'easy' problems of consciousness, and fail at addressing the real mystery at the heart of the conscious experience. And so for Chalmers, the mystery remains: why does all this physical and integrative processing of the brain produce an inner subjective experience? At present, it would seem that all purely reductionist brain based theories of consciousness produce purely mechanistic explanations about the functioning of systems, its structures, its dynamics, and the behavior it produces. While research investigating the NCC provides eloquent explanations for how we behave and how we function, when it comes to explaining the origins of the subjective experience, this hard question always remains unanswered. So, are we left at an impasse?

While the discovery of the origins consciousness has yet to emerge from our current scientific zeitgeist, it may be that we need some new and potentially radical ideas. Physicists have asserted that there are aspects of the physical universe that are fundamental, such as space, time and mass, and they postulate that our world is governed by fundamental laws such as gravity and quantum mechanics. Sometimes, however, the list of fundamentals expands. In the 19th century, James Clerk Maxwell discovered that electromagnetic phenomena could not be explained by space, time or mass. He proposed that electric and magnetic fields travel through space as waves, and thus he uncovered a new fundamental law of electromagnetic charge (Maxwell, 1865). Could it be that if there are no fundamental laws that explain consciousness, that maybe consciousness *itself* is a fundamental element of nature? Fundamentalist perspectives such as Panpsychism suggest that consciousness (the mind, or psyche) is a fundamental, matter inherent, universal and primordial feature of all things (Seager, 1995), and that the basic physical constituents of the universe have mental properties (Nagel, 1979). Panpsychism considers the mind as a mind in a world of mind, with notable scholars such as Chalmers, Koch, Whitehead, Jung, Schopenhauer, James, Wundt, Berkeley, Leibniz, Spinoza, Einstein, Bohm and many others having all identified with Panpsychism in one form or another.

While this may seem counter intuitive to Western scientific and reductionist logic, the idea that the human mind is continuous and fundamental is deeply integrated into most of the eastern philosophical and scientific perspectives and culture (Wallace, 1999). In fact, many of the fundamental insights regarding the origins and nature of consciousness that have come from the ancient eastern contemplative spiritual traditions, such as the Buddhists and Tibetans, have recently been evidenced in neuroscientific findings (Wallace, 2009, Lutz and Thompson, 2003). In many ways, the contemplative practitioners and Buddhist monks can be considered the 'astronauts of the inner world', having studied the human mind through intensely rigorous techniques and methods aimed at the pursuit of observing and understanding the subtle and fundamental aspects of consciousness. Chapter three will be dedicated to elaborating on these eastern contemplative perspectives in the context of recent research findings. However for philosophers such as Dennett, he believes that there is no hard problem of consciousness to start with. Dennett argues for a purely reductionist theory of consciousness, and suggests that our inner subjective experience of a movie is simply an illusion or form of confusion, and all that is necessary is a functional explanation of the brain in terms of strictly physical mechanisms (Cohen & Dennett, 2011).

1.3 Attention and Consciousness: What's the difference?

Can consciousness be defined by what we attend to? When we stop attending to an object, do we definitively lose consciousness of the specific features of that object? Scientific research within the domains of both consciousness and attention suggest that these psychological concepts are not only closely related, but also often conceptually overlapping. According to Dijksterhuis and colleagues (2006), "Whereas conscious thought refers to thought or deliberation while conscious attention is directed at the problem at hand, unconscious thought can be defined as thought or deliberation in the absence of conscious attention directed at the problem". While research over the decades has broken down many of the theoretical, ontological and conceptual aspects of consciousness (Block, 2005; Chalmers, 1996), the cognitive processes involved in attention have similarly been broken down into aspects such as orienting, filtering, and searching functions. They have been further delineated to the anterior and posterior neural circuits for endogenous (top-down) and exogenous (bottom-up) processes respectively (Buschman & Miller, 2007).

The top-down selective attention to an object brings into our awareness specific attributes. However, mental phenomenon such as decision making, language, and long-term goals are all aspects of consciousness that often fall outside of selective attention (Koch, Massimini, Boly, & Tononi, 2016). Current research suggests that consciousness and attention are two distinct but allied processes, each having their respectively distinct processes and neurobiological correlates (B. J. Baars, 1997; Crick & Koch, 2003; Stanislas Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Hardcastle, 1997; Koch & Tsuchiya, 2007; Lamme, 2003; Naccache, Blandin, & Dehaene, 2002; Tse et al., 2005; Bachman 2006). However, interesting research by Dehaene and colleagues (2006) suggests that top-down attention serves a fundamental prerequisite for the perception of an event, and that an event cannot be consciously perceived without it, and will remain consciously covert. Dehaene asserts that a subject must be able to report the observation of a stimulus in order to experience 'consciousness' of it, but that unconscious information can still influence decision-making processes (Figure 1; Del Cul, Baillet, Dehaene (2007)).

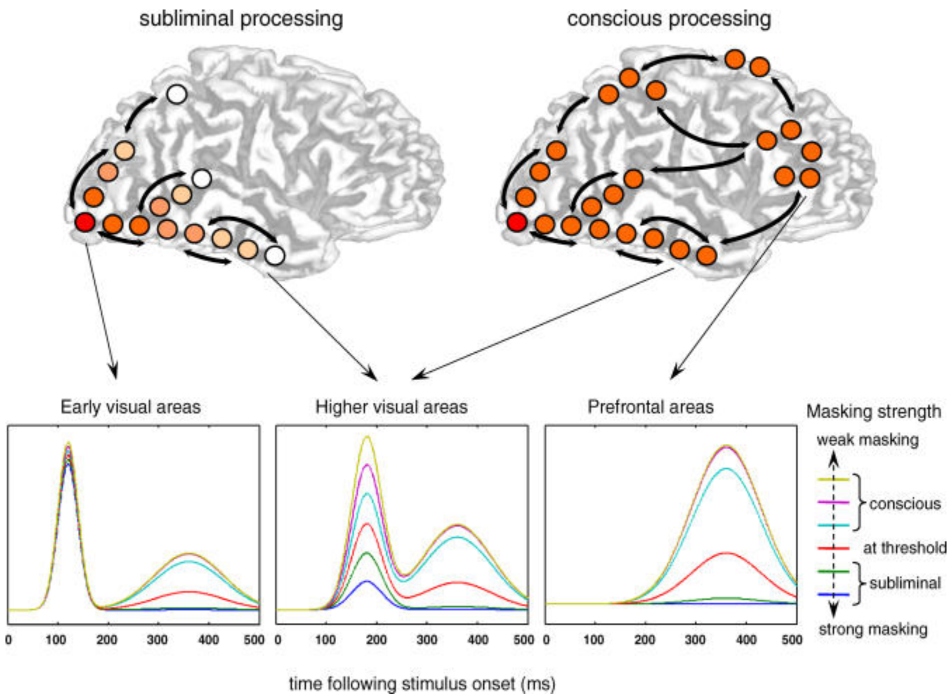


Figure 1. Del Cul, Baillet, Dehaene (2007). When a stimulus that is flashed is followed by a backward mask, subjects fail to perceive it unless the target-mask interval exceeds a threshold duration of about 50 ms. The Global Neuronal Workspace (GNWS) model of conscious access postulates that reverberating loops that spread across the frontal and parietal cortex are necessary for conscious experience. They argue that the conditions for consciousness for masked stimuli are not present because the mask interferes in the reverberating feedback signals, preventing the spread of activations throughout the cortex. Findings from their study suggest that subliminal processing can occur early on in the occipito-temporal pathway (<250 ms) and point to a late (>270 ms) and highly distributed fronto-parieto-temporal activation as the correlate of conscious reportability.

1.4 New theoretical models and perspectives of consciousness

1.4.1 The Global workspace model

One of the most prominent current theories of consciousness is the global workspace account of consciousness first put forward by Bernard J. Baars (1988). Scientists Stanislas Dehaene and Jean-Pierre Changeux have further developed the model from a neural perspective (Figure 2; Global Neuronal Workspace model; Dehaene & Changeux, 2000; Dehaene, Kerszberg, & Changeux, 1998; Dehaene & Changeux, 2011; Dehaene, Changeux, & Naccache, 2011) which uses a computer model of the known NCC to simulate neural networks

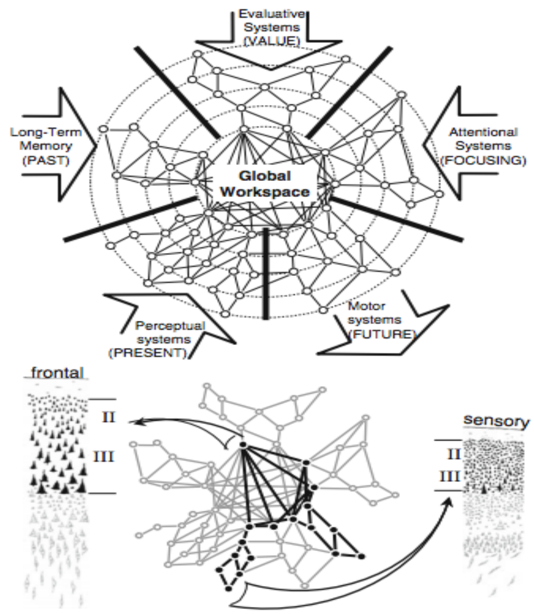


Figure 2. The Global Neuronal Workspace model (GNW) proposes that associative perceptual, motor, attention, memory and value areas interconnect to form a higher-level unified space where information is broadly shared and broadcasted back to lower-level processors. The GNW is characterized by its massive connectivity, made possible by thick layers II/III with large pyramidal cells sending long-distance cortico-cortical axons, particularly dense in PFC (Dehaene et al., 1998; Dehaene et al., 2011) .

that are then used to identify the activity and signatures of the brain's higher cognitive functions, namely consciousness, executive functioning, and decision making processes (Dehaene & Changeux, 2000). This model assumes that competing neural coalitions, involving both the frontal and sensory areas determine states and modes of conscious experience (Dehaene & Changeux, 2011). Further research implementing their model has shown that prevailing coalitions or networks initiate oscillations through primary long-range connections to the frontal then parietal cortex, facilitating activity that maintains both primary and peripheral activations (Koch, 2004). While it is now ubiquitous in neuroscience that some brain areas control activations and reactivations in other areas (Damasio & Meyer, 2008), Curtis and D'Esposito (2003) established the concept of 'reciprocal control', implicating frontal areas of the workspace network in the control of activations throughout sensory and spatial areas. According to Dehaene, the subjective experience of consciousness results from a piece of information selected based on its significance to a current goal state, which is then amplified and broadcast globally to distal areas of the brain (Stanislas Dehaene & Changeux, 2011). However, the Global Neuronal Workspace model is relatively abstract when compared to more traditional models coming from research in computational neuroscience and neurobiology. Most notably because the theory focuses almost exclusively on a small number of brain regions and does not address whether there may be other processes involved in the mechanisms underlying what determines what we consciously experience (Torrey, 2009).

1.4.2 Integrated Information Theory

The human brain is arguably the most intricate and complex information-processing system known to man. The highly integrated nature of neuronal computations has lead neuroscientists such as Giulio Tononi to suggest that human consciousness is directly associated with the complexity of a given physical system. According to Integrated Information Theory (IIT), the degree of consciousness in a given physical system is determined by its causal properties and features, and therefore is intrinsic to any and all physical systems (Tononi, Boly, Massimini, & Koch, 2016). IIT posits that the degree or level of consciousness of a system at a given point in time is a product of how many possible states it expresses at that time and how closely integrated its states are (Tononi & Edelman, 1998a, 1998b).

In essence, IIT moves from phenomenology to mechanism by attempting to identify the essential properties of conscious experience and, from there, the essential properties of conscious physical systems (Giulio Tononi et al., 2016). The theory also accounts for the quantity and the quality of an individual experience, and then uses a calculus called 'phi' to determine whether or not a particular physical system is conscious, and of what. IIT assumes that consciousness is a fundamental element existing in all physical systems that have specific causal properties. The assumptions of IIT result in the notion that there are levels of consciousness, that can be represented by their respective value of phi, and that phi is present in simple physical systems as well as in all biological organisms (Giulio Tononi & Koch, 2015).

1.4.3 The Unified Theories of Consciousness

"There is a fundamental assumption within modern Neuroscience: all experience is a consequence of the human brain's structure and its correlative activity. The relationship between experience and brain has been described as dualistic, parallel or reducible. Either from the perspective of extreme idealism that assumes all matter is a consequence of thought or extreme materialism that assumes all thought is determined by matter the reference has been and must be consciousness. This millennial deliberation of a thesis and an antithesis concerning "spirit" and "substance" is still manifested as the contemporary apparent dualism between matter and energy. The conflict converges within the concept of consciousness" (Persinger, 2014).

Since none of the existing approaches seem to have uncovered the fundamental and universal properties of conscious systems, could it be that consciousness is indeed a fundamental property of the universe (and not a matter-inherent property as panpsychism would suggest)? Joachim Keppler (2016) asserts that the brain "extracts the variety of phenomenal nuances from a ubiquitous sea of consciousness", functioning as a form of universal filtering mechanism (Keppler, 2013). According to this model, consciousness is neither emergent (reductionist) nor assembled (panpsychism) but rather a highly specialized filter of consciousness, and the whole range of phenomenal qualities is built into an all-pervasive background field of consciousness that is in permanent interaction with matter (Keppler, 2016). According to Keppler, the functioning of the brain depends on a universal mechanism that enables ordered states in an all-pervasive substrate of consciousness. Interestingly, these theories are ubiquitous with Eastern philosophical perspectives that insist on consciousness as the primary *phenomenon,* and that material objects have no intrinsic reality (Ricard & Thuan, 2004; Keppler, 2016).

Within the field of quantum physics, Unified Field Theory postulates that all elementary particles and fundamental forces constitute a single field in which all physical systems are embedded. Initially seeded by Einstein and later scientifically evidenced by David Bohm, arguably the two most influential theoretical physicists of the 20th century, they both believed that everything in the universe is relative, and the existence of different worlds and forms and phenomena can only be accounted for in terms of relativity (Stanford Encyclopedia of Philosophy, 2001). Bohm's theories of superstrings and compactification have been vetted over the years, all of his complex and numerical models point to the same fundamental conclusions: everything in our universe blossoms out from an underlying unity, and that the dualistic perspective of matter and energy is an illusion (Bohm, 1986). In the words of Benjamin Libet, "a conscious mental field may be viewed as somewhat analogous to known physical fields… however it cannot be observed directly by known physical means" (Libet, 1994).

1.5 The Neural Correlates of Consciousness

We humans perceive the physical world through our senses, and convert visual and sensory information into electrical signals that then transmit this information into the central nervous system, and eventually the brain. Research over the last several decades has uncovered many of the Neural Correlates of Conscious (NCC) experiences, which refer to the relationship between the experiences reported by subjects and the activity that simultaneously takes place in their brains, or in other words, the NCC seek to link objective, observable, neural activity to subjective, unobservable, conscious phenomena (Figure 3; Koch, 2004). According to

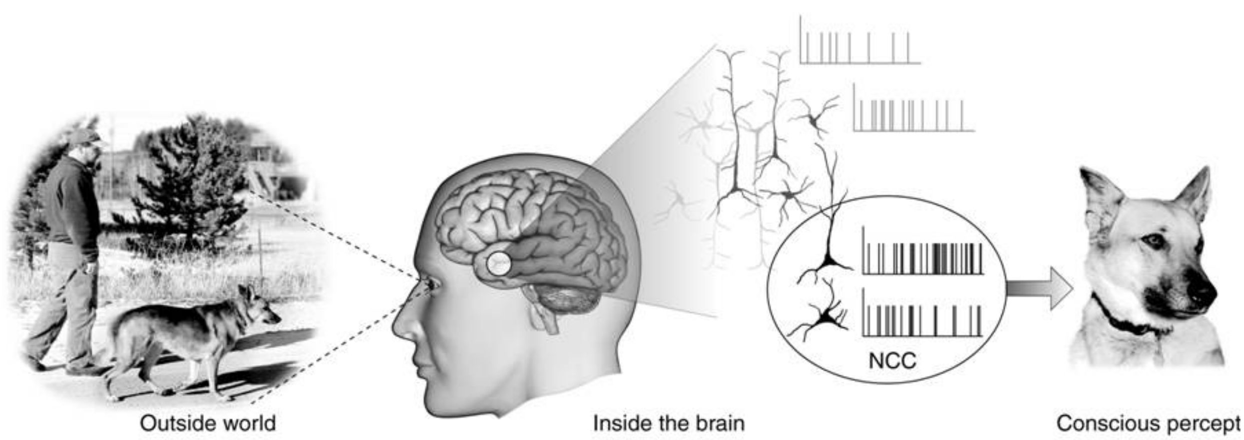


Figure 3. The Neuronal Correlates of Consciousness (NCC) consist of sets of neural structures and events (both large and small) for any given conscious percept or explicit memory. It has been proposed that conscious percepts involve the synchronization of action potentials in neocortical pyramidal neurons (Koch, 2004).

Koch and colleagues (2016) the content-specific NCC refers to the various neural activations that correspond to specific states or types of phenomenological experience. The larger NCC would include all of the underlying mechanisms that together support overall consciousness, and would represent a union of all the individual and specific contents. Furthermore, the 'background conditions' for being conscious (basic functions that enable consciousness without immediately influencing the content) such as a glucose and oxygen levels additionally modulate and facilitate cortical excitability (Stender et al., 2015).

Accumulating research findings have begun to identify some of the neural substrates that may underlie and facilitate conscious perception. These regions include the brainstem, hypothalamus, and the basal forebrain that projects excitatory connections to thalamic neurons (Parvizi & Damasio, 2001). It has been proposed that primary thalamic nuclei facilitate network wide communication, and may serve as a template for the emergence of consciousness (Moruzzi & Magoun, 1949; Parvizi & Damasio, 2001, 2003). While the underlying neural mechanisms for both attention and consciousness are undeniably similar (Catherine Tallon-Baudry, 2012), it has been suggested that coordinated neural activity across distributed cortical areas may be what gives rise to consciousness. The synchronization of oscillatory activity has been proposed as a neural mechanism that could facilitate communication across and within neural populations (Fries, 2005). Singer & Gray (1995) found that two neural groups, both that encoded unique features of a given stimulus (i.e. firing rate), may signal in time to one another that they are processing related pieces of information through the synchronization of their activity at the population level. These findings have led some researchers to assume that the synchronization of oscillations may function as a neural mechanism involved in the emergence of consciousness. Furthermore, recent research has demonstrated that differing areas and functions of the brain have shown preferred oscillating frequencies (Buzsaki, 2004; Cavanagh & Frank, 2014; Cohen, 2014). It has been suggested that cognition and perception may be a product of the succession of cycles which mirror the synchronization of the underlying oscillations, and that there may exist several rhythms of perception that would depend on the specific mode, task and neural features (Figure 4; VanRullen, 2016).

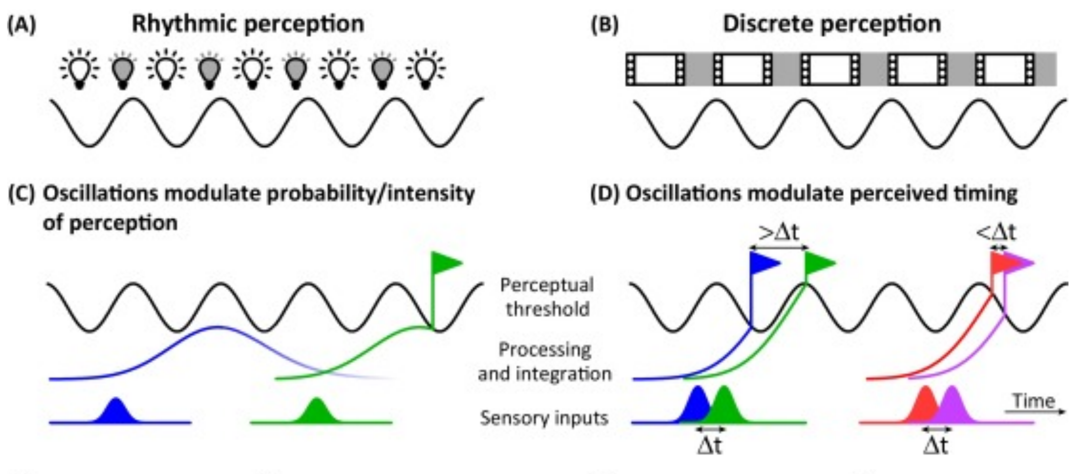


Figure 4. This figure shows examples of both rhythmic and discrete perception. (A) An illustration of rhythmic perception, suggesting that efficient neuronal, sensory, perceptual, or cognitive processing is facilitated by specific phases of each oscillatory cycle (white light bulbs), whereas the same process is less efficient at the opposite phase (dimmer light bulbs). (B) Discrete perception suggests that neuronal, sensory, perceptual, or cognitive events are separated into discrete epochs (like the snapshots of a video clip, depicted here above the oscillation. (C) For two identical weak sensory inputs, integration may or may not reach perceptual threshold, depending on the phase of stimulus presentation. (D) Stronger sensory inputs consistently reach perceptual threshold, but at slightly different times. In this illustration a simple rhythmic modulation of neuronal processing thus results in a periodic modulation of both the probability/intensity of perception (VanRullen, 2016).

An emerging consensus within experimental studies have linked visual consciousness in humans with both gamma (~30–90 Hz) and beta (~15–30 Hz) band oscillatory synchrony, with findings demonstrating that stimuli are only consciously perceived when oscillations in the gamma-band (30–100 Hz) are present in posterior regions (Luo et al., 2009; Schurger, Cowey, Cohen, Treisman, & Tallon-Baudry, 2008; Wyart & Tallon-Baudry, 2008, 2009). During bistable perception, increased gamma-band oscillatory synchrony was time locked to perceptual transitions (Doesburg, Kitajo, & Ward, 2005). In other domains, painful somatosensory stimuli induced somatosensory gamma-band oscillations time locked to pain ratings (Gross, Schnitzler, Timmermann, & Ploner, 2007). While both attention and consciousness have been associated with gamma-band oscillatory synchrony, it has also been linked to other types of cognitive functioning such as feature binding, memory, and learning (Fries, 2009; Jensen, Kaiser, & Lachaux, 2007; Tallon-Baudry, Kreiter, & Bertrand, 1999; Tallon-Baudry, 2009). Research would suggest that oscillatory synchrony may function as a form of code, that can be implemented in any given type of cognitive activity (Catherine Tallon-Baudry, 2012). This is conceptually very similar to the fundamental mechanisms underlying neuronal spiking and their respective role in neuron-to-neuron signaling (Pereira & Furlan, 2010).

According to the seminal scientist György Buzsáki, the notion that "*structure defines function*" is the fundamental principle that best describes the human brain. He argues that *"the architecture of different brain regions determines the kinds of computations that can be carried out, and may dictate whether a particular region can support subjective awareness…. self-organized, or so called 'spontaneous' activity is the most striking and yet perhaps least appreciated feature of the cerebral cortex. Without inhibition, excitatory activity caused by any one stimulus would ripple across the entire neuronal network and a confused jumble of overlapping signals would result. Inhibitory interneurons and the rhythms they generate can temporally and spatially structure the activity of excitatory cell assemblies to ensure that information flows to just the right place at just the right time*" (György Buzsáki, 2007).

1.6 Altered States of Consciousness

Altered States of Consciousness generally refer to mental states that deviate from what is considered to be a normal waking state of awareness (Figure 5; Laureys, Perrin, & Brédart, 2007; Ludwig, 1966). A subclass of these mental states can be voluntarily induced through techniques such as meditation, hypnosis and lucid dreaming, as well as through psychoactive substances or pharmacological agents (Tart, 1969a, 1969b; Revonsuo, Kallio, & Sikka, 2009). Consistent reports of profound personal, psychological and spiritual insight during intentionally induced altered states of consciousness suggest that certain features of these experiences may share common underlying neural activity, and may have therapeutic applications in the treatment of some psychiatric disorders such as major depression and substance dependence (dos Santos et al., 2016). In a study investigating the EEG activity of Ayahuasca consumption, Schenberg and colleagues (2015) found a significant effect of both reduced alpha power (8–13 Hz) 50 minutes after

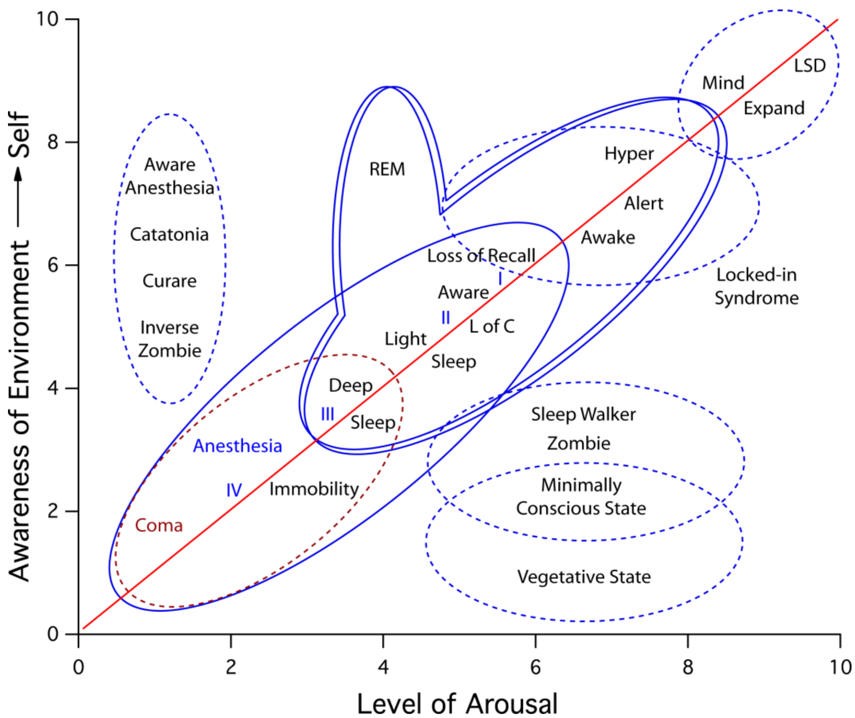


Figure 5. This figure illustrates of the two main features defining conscious states: arousal (i.e., the level of consciousness) and awareness of environment and self (i.e., the content of consciousness). The red line reflects the correlation between awareness and the degree of arousal (consciousness). Experienced as a continuum along this correlation (red line), these states also include the paradoxical dream state during REM sleep. Patients in pathological or pharmacological coma states are considered to be unconscious as they are non-responsive (image adopted by the Stanford Institute for Neuro-Innovations and Transformative Technology from Laureys, Perrin, & Brédart, 2007).

consumption and increased slow and fast gamma power (30–50 and 50–100 Hz, respectively) between 75 and 125 minutes after Ayahuasca ingestion. The effects were observed in the left fronto-temporal, left centro-parieto-occipital and right frontal cortices, in addition the fast-gamma frequencies in the right occipito-temporal electrodes. These findings are consistent with previous research showing increased gamma activations in the left occipito-temporo-parietal areas (Don et al., 1998) alongside widespread increases in coherence (Dos Santos et al., 2012). There is a general consensus that the functional role of synchronized gamma oscillations is linked to the binding and integration of neural representations and cognitive functions such as attention and memory (Fries, 2005; Jensen et al., 2007). Furthermore, the synchronization in gamma activity across the fronto-parietal networks which facilitate the kind of neural activity leading to reportable subjective experience (Dehaene et al., 2011). Schenberg and colleagues (2015) have suggested that these gamma power increases may be related to an increased metacognitive awareness of one's mental states, possibly including increased awareness of memories and intentions through potentiated visual imagery, and highlight the potential therapeutic benefits of such experiences in the treatment of addiction, depression, anxiety, post-traumatic stress disorder and others (Figure 6).

Interestingly, similar gamma power increases have recently been found during reports of lucid dreaming. Lucid dreams are dreams during which the dreamer is aware that he/she is dreaming, and can control dream characters, narrative, and environments, and can be considered a state of sleep wherein primary and secondary states of consciousness coexist, and is a phenomenon that is most likely unique to humans (Voss et al., 2014). Dream Yoga, developed by the Tibetan Buddhists over a thousand years ago is a vast system of teachings and practices which use the power of lucid dreaming to explore the nature of the conscious and subconscious mind while simultaneously deconstructing the illusory nature of permanence, unlocking the door to enlightenment (Wallace, 2006). During lucid dreams, it is thought that aspects of what Voss and colleagues (2014) refer to as 'secondary consciousness' can simultaneously occur alongside the normal REM sleep consciousness, facilitating awareness of dream while it continues. In their recent Nature publication, Voss and colleagues showed that this self-awareness claimed by avid lucid dreamers, could be induced during dreaming through frontal tACS stimulation in the slow-gamma band (Voss et al., 2014). Fronto-temporal 40-Hz band activity significantly correlated with measured lucidity following stimulation, suggesting that lower gamma-band activity is related to increased self-reflective awareness. Interestingly, experienced lucid dreamers can successfully execute predetermined actions and various forms of signaling indicating specific times of specific dream events whilst asleep. These studies have allowed the inference of precise psychophysiological correlations and the methodical testing of various hypotheses during Lucid Dreaming (La Berge, 1980). Interestingly, these gamma increases are also found during other introspective states such as meditation (de Freitas Araujo et al., 2012).

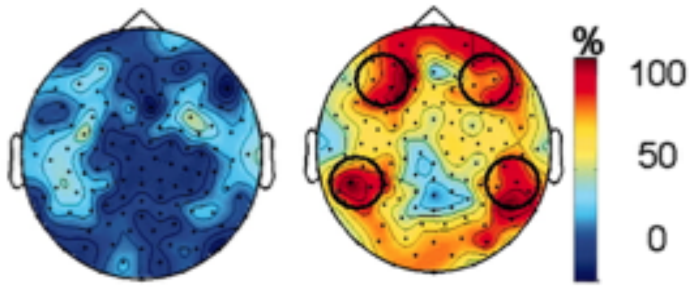


Figure 6. This figure shows the absolute gamma power and long-distance synchrony during mental training. Scalp distribution of gamma activity during meditation. The color scale indicates the percentage of subjects in each group that had an increase of gamma activity during the mental training. (Left) Controls. (Right) Practitioners. An increase was defined as a change in average gamma activity of >1 SD during the meditative state compared with the neutral state. Black circles indicate the electrodes of interest for the group analysis (Lutz et al., 2004).

Cahn et al. (2010) found that the cross-experimental session occipital gamma power was significantly larger in meditators with more than ten years of daily practice, and that the meditation-related gamma power increase was similarly the strongest in such advanced practitioners. These findings suggest that long-term Vipassana meditation contributes to increased occipital gamma power related to enhanced sensory awareness. In a separate study, long-term Buddhist practitioners were able to self-induce sustained high-amplitude gamma-band (25-42 Hz) oscillations and phase-synchrony, most notably over the lateral frontoparietal electrodes during a period of meditation (Figure 6; Lutz, Greischar, Rawlings, Ricard, & Davidson, 2004).

Additional research has shown that during states referred to as fruition, a known stage within the Mahasi School of Theravada Buddhism in which meditation practitioners experience a culmination of contemplation-induced stages of consciousness, global long-range gamma (25–45 Hz) synchronization was found, when compared to the EEG recorded during the background meditation (Berkovich-Ohana, 2015). The authors suggest that long-range global gamma synchronization may serve as an underlying neural mechanism enabling the enhanced metacognitive awareness that is necessary for the deconditioning of habitual mental patterns, and propose that these processes may facilitate what the Buddhist traditions refer to as enlightenment or liberation.

While significant progress has been made in research investigating various forms and types of altered states of consciousness (that extends far beyond the scope of this thesis), due to advancements in experimental methodologies and neuroimaging techniques a relatively new field of research has been emerging over the last decade investigating a state of consciousness referred to as mind wandering. Mind wandering is of increasing to consciousness scholars due to its prevalence during conscious waking hours (~50% if waking hours; Kilingsworth and Gilbert, 2010), when subjects are lying at rest in an MRI scanner (Raichle et al., 2001), the apparent similarity of recruited brain areas across subjects (Raichle and Raichle, 2001), and the potential role that it serves in memory consolidation, learning, emotional affect (Fox, Thompson, Andrews-Hanna, & Christoff, 2014), and will be discussed at length in the subsequent chapter.

Chapter 2: Mind Wandering and the last 10 years of Research

2.1 An Introduction to Mind Wandering

One of our most unique human attributes is our capacity for a vastly complex inner landscape, and our ability to recall, generate, and manifest insight based on experience and then predict out into the future. While an elaborate internal dialogue is fundamental to our human experience, this ongoing narrative can surface unknowingly, or at inopportune points in time. This phenomenon is commonly referred to as mind wandering or self-generated thought and is the experience of thoughts involuntarily drifting to topics unrelated to the task at hand, often occurring under conditions where external demands on our attention are low (Smallwood & Andrews-Hanna, 2013; Smallwood, Ruby, & Singer, 2013). Early pioneers such as Singer, Klinger and Antrobus began researching topics such as daydreaming in the late 1960s and early 1970s (Antrobus et al., 1966, Klinger, 1978), and it was shortly thereafter that research began studying the mind's unique capacity to stray from the external world and events, generating streams of thought disconnected from and unrelated to the surrounding environment (Giambra, 1989; Teasdale et al., 1995). Over the past decade, widespread scientific attention has been given to the topic of mind wandering, facilitating a shift away from earlier skeptical attitudes towards the scientific relevance of internal experience passed down from the behaviorist era (Callard, Smallwood, & Margulies, 2012; J. D. Cohen & Schooler, 1997). It was not until the early 2000s that Schooler and Smallwood first brought the concept of mind wandering into the field of experimental psychology (Schooler, 2002) using existing tasks in psychophysics (Rosvold et al., 1956; Robertson et al., 1997). The study of mind wandering in experimental psychology, and more recently in behavioral neuroscience has been growing exponentially over the past 10 years. First-person accounts reveal mind wandering to be a vastly complex phenomenon involving a multitude of sensory modalities, time domains, and intellectual and creative content (Andrews-

Hanna, Reidler, Huang, & Buckner, 2010; Fox, Nijeboer, Solomonova, Domhoff, & Christoff, 2013; Fox et al., 2014; Klinger, 2009, 2013; McMillan, Kaufman, & Singer, 2013; Smallwood & Andrews-Hanna, 2013; Klinger, 1990). While the neuroscientific study of mind wandering lags far behind much of the phenomenological work, a general picture of brain activity involved in mind wandering is beginning to emerge, implicating broad neural networks (Fox et al., 2015).

One of the important distinguishing elements of self-generated thoughts is that intrinsic changes are directly responsible for the contents of these thoughts, which can be either coupled or decoupled from the external perceptual events taking place in the surrounding environment (Smallwood & Schooler, 2015). In a seminal study by Killingsworth and Gilbert (2010) participants reported being engaged in task-unrelated thought during almost half of their waking hours. While research has demonstrated that mind wandering is essential for creativity and memory consolidation (Baird et al., 2012), under less desirable circumstances excessive mind wandering is associated with problems in learning, rumination, anxiety, and depression (Poerio, Totterdell, & Miles, 2013; Smallwood, Fishman, & Schooler, 2007; Smallwood, McSpadden, & Schooler, 2007). As discussed by Smallwood and Schooler (2015), mind wandering episodes can contain a mixture of distinct features which contribute to their experiential nature, and that can determine either the beneficial or negative aspects of mind wandering. It has been suggested that mind wandering serves as a mnemonic process involving a variety of episodic forms of autobiographical memory, facilitating an “autonoetic consciousness”, unique to the human capacity of the awareness of self (Tulving, 2005; Vago & Zeidan, 2016). Tulving (2005) suggests that it is this, which provides us the fundamental framework for the advancements in technology, society, our intelligence, and the intrinsic abilities necessary to navigate our complex environment. Given the pervasive and complex nature of mind wandering, the lack of direct experimental control, the covert nature of self-generated thoughts, and the bias of introspective evidence, exploring the behavioral and neural dynamics underlying mind wandering, using new and novel methods is a crucial and necessary step towards understanding how the brain produces what William James first referred to as the ‘stream of consciousness’ (Figure 7; James, 1890).

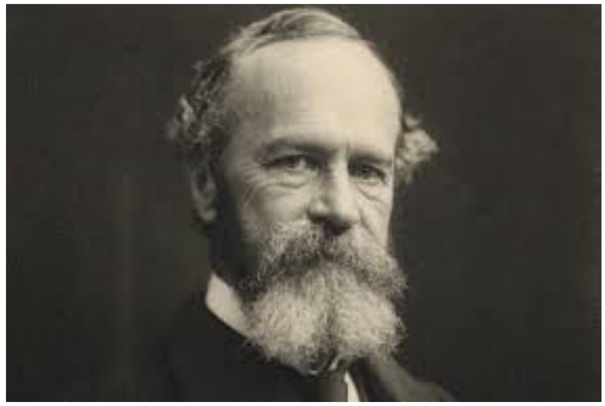


Figure 7. William James (1842 -1910) was one of the great American philosophers and a distinguished professor of philosophy and psychology at Harvard University, famous for what he delineated as the 'five generic characteristics' of mind:" (1) all thought is owned by some personal self; (2) all thought, as experienced by human consciousness, is constantly in flux and never static; (3) nevertheless, there is an ongoing continuity of thought for every thinker, as it moves from one object to another (like the alternating times of flight and perching in a bird's life), constantly comprising shifting foci and the contextual fringes within which they are given; (4) thought typically deals with objects different from and independent of consciousness itself, so that two minds can experience common objects; and (5) consciousness takes an interest in particular objects, choosing to focus on them rather than on others" (James, 1890).

2.2 The Content of Self-Generated Thought

Research has shown that there are distinct psychological correlates for mind wandering about the past and future (Tulving, 2002). Several studies have demonstrated a bias toward future thinking in daily life and laboratories across a range of countries (Baird, Smallwood, & Schooler, 2011; Iijima & Tanno, 2012; Ruby, Smallwood, Engen, & Singer, 2013; Smallwood et al., 2011; Smallwood, Nind, & O'Connor, 2009; Song & Wang, 2012; Stawarczyk, Majerus, Maj, Van der Linden, & D'Argembeau, 2011), with future oriented mind wandering evaluated as being interesting and associated with positive mood (Franklin et al., 2013). However, Killingsworth & Gilbert (2010) showed that mind wandering in general was associated with a reduced sense of well being, particularly for mind wandering events focused on the past. Further studies have also demonstrated similar findings to those of Killingsworth & Gilbert, showing that mind wandering focused on the past directly led to low moods in laboratory conditions (Ruby et al., 2013; Smallwood & O'Connor, 2011; Stawarczyk, Majerus, & D'Argembeau, 2013) and in daily life (Poerio et al., 2013). Psychopathological states such as anxiety and depression have been linked to self-generated experiences that have past-oriented and perseverative features (Ottaviani & Couyoumdjian, 2013; Ottaviani, Shapiro, & Couyoumdjian, 2013), while unaware mind wandering was associated with higher levels of depression (Deng, Li, & Tang, 2014). The *Content regulation hypothesis* (Andrews-Hanna, Smallwood, & Spreng, 2014; Smallwood & Andrews-Hanna, 2013) suggests that one of the direct consequences of mind wandering is its established relationship to negative affect, with research directly linking premature aging with negative and past oriented mind wandering episodes (Epel et al., 2013). The aforementioned studies all suggest a direct interaction between mood and content. The *Context regulation hypothesis* proposes that mind wandering is more likely to occur under conditions in which the demands on external attention are low (Schooler et al., 2011), with an increase in mind wandering leading to poor performance on demanding tasks such as reading. Thus mind wandering may function to optimize cognitive resource allocation by limiting mind wandering to circumstances not requiring continuous attention.

2.3 Methods of Measurement

The majority of research studies which aim to capture mind wandering events have implemented a technique known as experience sampling (Kahneman et al., 2004). Various methods of experience sampling have been implemented in experimental studies in order to capture internally generated thoughts during task performance. The Probe-Caught method entails that subjects have to respond with (detailed) information regarding the contents of their consciousness at a given point in time (Brandmeyer & Delorme, 2016; Seli, Carriere, Levene, & Smilek, 2013; Seli, Cheyne, & Smilek, 2013; Smallwood & Schooler, 2006; Smallwood et al., 2003). The Self-caught method entails that the subject reports the occurrence of mind wandering at the point in time when they have become aware that their thoughts have drifted away from the task at hand (Braboszcz & Delorme, 2011; Smallwood & Schooler, 2006). The Retrospective method of experience sampling includes data such as questionnaires that are collected after the completion of a given task. These methods provide the advantage of allowing subjects to engage in the natural processes and time course of performing a given task (i.e. without being interrupted by an experience sampling probe every few minutes), however these measures are often skewed by retrospective biases and large differences across subjects (i.e. reading; Barron, Riby, Greer, & Smallwood, 2011; Smallwood et al., 2012). Smallwood and Schooler (2015) have argued that all of the aforementioned methods of measurement predominantly address the contents of thought a specific point in time, but they elucidate very little regarding the dynamic events that bring about the given mental state being measured. Thus, the development of more nuanced methods are necessary to learn how mental states are related, and evolve over time.

2.4 Neural mechanisms underlying mind wandering

2.4.1 Magnetic Resonance Imaging and Episodic Memory

Research in functional magnetic resonance imaging (fMRI) has begun to identify the neural networks largely contributing to mind wandering and the generation and maintenance of self-referential thought processes. The default mode network (DMN), comprised of the medial prefrontal cortex (mPFC), posterior cingulate cortex (PCC), superior and inferior frontal gyri, medial and lateral temporal lobes and the posterior portion of the inferior parietal lobule, shows consistent activations during both probe-caught and self-reported episodes of mind wandering (Figure 8).

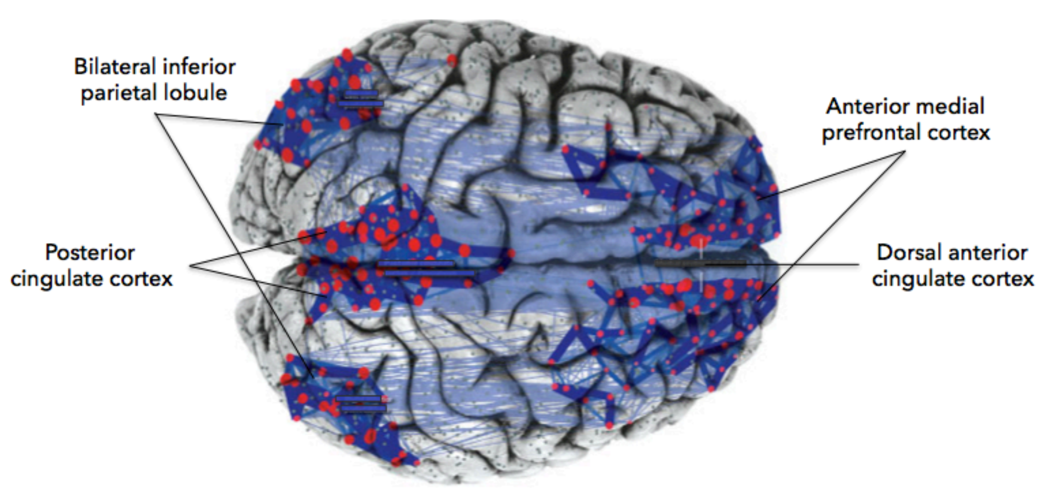


Figure 8. Key regions that together comprise the DMN (Carhart-Harris & Friston, 2010)

It has been shown that mind wandering episodes typically involve thinking about oneself, others, remembering the past, and planning for the future (Buckner, Andrews-Hanna, & Schacter, 2008; Gusnard, Raichle, & Raichle, 2001; Raichle et al., 2001). This ability to mentally move through time has been referred to as 'mental time travel' and has been directly linked to the episodic memory processes thought to generate mental content (Tulving, 2002). The relationship between mind wandering and the episodic memory system is supported by ample fMRI findings showing increased DMN activations during studies in which subjects imagine being in another place or time (Addis et al., 2012), or are instructed to think about themselves (Kelley et al., 2002; Macrae, Moran, Heatherton, Banfield, & Kelley, 2004; K. J. Mitchell et al., 2009).

New findings have linked mind wandering to activations in the frontal parietal control network (FPC), a network comprised mainly of the anterior cingulate cortex (ACC), mPFC, amygdala, PCC and the insula, and has been proposed to modulate top-down mechanisms involved in sustaining both endogenous and exogenous forms of attention allocation (Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013). Spreng et al. (2013) suggest that the FPC facilitates goal-directed cognition, which functions as a gatekeeping system by moderating the dynamic balance between activations in the DMN and the dorsal attention network (DAN). It might also facilitate alternating or competing goal representations while maintaining directed attention to a given external task (i.e. driving, running; Spreng, 2012). Concurrent activations in both the DMN and core regions of the executive functioning network (dorsolateral mPFC, ACC), networks that were traditionally considered independent, anti-correlated, and thought to compete for cognitive resources, have recently been shown to co-activate during mind wandering episodes, and increasingly so when subjects reported being unaware of their mind wandering (Figure 9; Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Fox et al., 2015).

Interestingly, emphasis on the flexible monitoring of ongoing experience during meditation is thought to be responsible for the increased functional connectivity in DMN activations observed in expert meditation practitioners trained in internally guided forms of sustained attention (Jang et al., 2011; Tang, Hölzel, & Posner, 2015). Taken together these findings support the notion

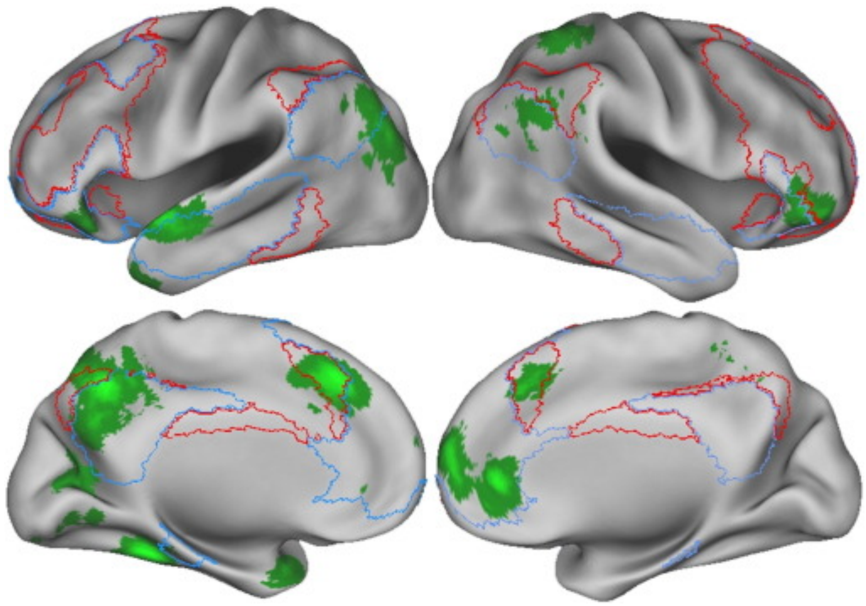


Figure 9. Meta-analytic clusters of brain activity that have been linked to mind wandering (green clusters), as compared to the DMN (blue) and the frontoparietal control network (red). Meta-analytic activity associated with mind wandering (and its associated activity) overlaps with both the frontoparietal control network and the DMN (Fox et al., 2015).

that both internally and externally directed forms of cognitive activity may recruit the DMN, as well as some overlapping regions of the executive networks.

2.4.2 Electroencephalography Findings and Perceptual Decoupling

Although the field of EEG analysis of mind wandering is still in its infancy, EEG findings have shown spontaneous fluctuations between two distinct and supposedly opposite modes during resting-state brain activity (Laufs et al., 2006). One of these modes is characterized by the presence of slow oscillations of 3–7 Hz (theta activity), which are associated with reduced levels of vigilance. The other mode is characterized by the presence of fast oscillations of 12–30 Hz, which are usually associated with high vigilance levels. These spontaneous patterns of increased and decreased theta activity have recently been associated with periods of mind wandering and periods of concentration in a study by Braboszcz & Delorme (2011). During a breath awareness task in which subjects used the self-report method to mark mind wandering events, they showed an increase in occipito-parietal theta and fronto-central delta during mind wandering (Figure 10), and propose that these findings may be related to the increased BOLD activity frequently observed in fMRI studies studying the DMN networks. In a recent study by Schooler et al. (2011), they explored the sensory decoupling that occurs during mind wandering, and whether it was mediated by the phase of ongoing cortical oscillations across one or more frequencies. This was done by analyzing the impact of task-unrelated thought on phase-locking of cortical activity to sensory stimuli during a vigilance task. Additional EEG studies provide supporting evidence for the notion that cortical phase-locking is linked to task-related attention (Baird, Smallwood, Lutz, & Schooler, 2014). Given the reductions of attentional resources allocated to the external environment during mind wandering, perceptual decoupling would therefore explain why these temporally fluctuating self-generated states can persist, leading to decreased task performance

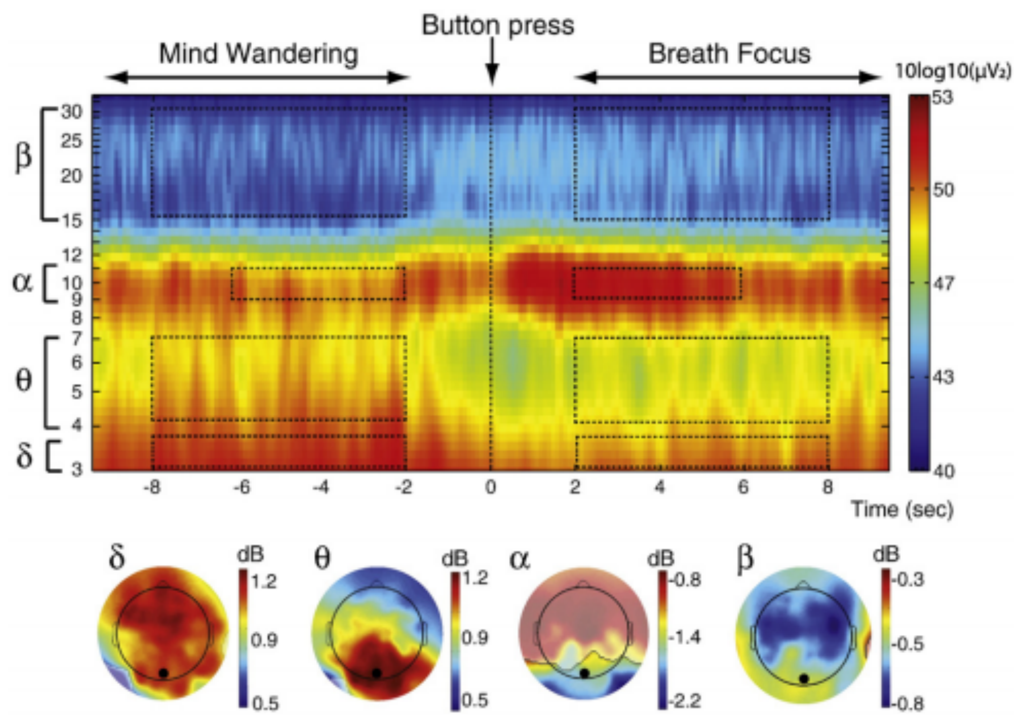


Figure 10. Time frequency analysis of EEG data time-locked to metaconsciousness event–button press (transition from mind wandering to breath focus) shows a significant influence of the subject's attentional state at all frequency bands from 2 to 25 Hz at electrode site Oz (taken from Braboszcz and Delorme, 2011).

(Kam & Handy, 2013;mallwood, 2013). Specifically, a link between phase-locking and fluctuations in an endogenous attentional state have been suggested by recent investigations examining the impact of training in focused attention meditation on phase-locking to stimuli in sustained attention tasks (Slagter, Lutz, Greischar, Nieuwenhuis, & Davidson, 2009). It was hypothesized that the mental training induced increases in phase-locking were related to the capacity to sustain task-related attentional focus and a reduced tendency to engage in task-unrelated thoughts. These findings suggest that techniques such as meditation that train the active engagement and directing of our attention, may impact the frequency and or the detection of mind wandering events. Given the findings by Kilingsworth and Gilbert (2010) suggesting that mind wandering occurs ~50% of the day, meditation practice may not only enhance the awareness of ongoing mind wandering, but increase the awareness and subsequent regulation of other sensory and cognitive processes. The following chapter will provide an overview of the ongoing research of mediation and contemplative practice and its important role in advancing the study of consciousness.

Chapter 3: The Rise of Contemplative Neuroscience

3.1 The Contemplative Revolution of Neuroscience

The majority of evidence from fundamental neuroscience research points towards the conclusion that consciousness reflects a series of perceptually cyclical and discrete neural processes (VanRullen, 2016), however our direct perception is that of a continuous and unified experience. According to William James, if we truly want to scientifically study consciousness, then like Galileo, Planck, Einstein, and Darwin, all of whose discoveries were rooted in rigorous, exhaustive, and precise 'observation' of the phenomenon they studied, we too must rigorously observe our personal experience of consciousness by means of introspection (James, 1890). For scientists such as Alan Wallace, in order for a science of consciousness to exist, it can only progress after the establishment of the necessary means and refined instruments that can measure and observe consciousness with rigor and precision. Wallace argues that the only instrument humanity has ever possessed for directly observing the mind or consciousness, is the mind itself, thus the mind itself is the instrument in need of refining. When attention is not trained, it is habitually prone to mind wandering, agitation and dullness, thus, if the mind is to be used as the instrument for exploring and experimenting with consciousness, these dysfunctional traits need to be replaced with attentional stability and vividness (Wallace, 2003). Like the refined telescope that Galileo developed to study the solar system with great detail, around 5000 years ago and long before the Buddha, a group of Indian contemplatives developed the initial methods for obtaining deeper levels of insight into the nature of the mind and consciousness by cultivating highly focused, stable and sustained attention, or 'Samadhi' (Wallace, 2014). The Buddha later went on to refine, advance and accelerate rigorous methods for stabilizing attention by using them in new and novel ways, much like Galileo (Wallace, 1999).

Over the last few decades, in parallel to the study of consciousness, we have witnessed an explosion of interest in and research on the mediating effects of meditation and mindfulness based practices and therapies on the brain, body, and overall health (Figure 11). Contemplative neuroscience is a young but rapidly growing multidisciplinary field investigating the underlying neural mechanisms of these ancient contemplative traditions and practices, alongside their physical, psychological, and neurological manifestations. When contextualized and translated into western scientific terms, meditation focuses on training attention in order to bring mental activity under improved voluntary control. Through the observation of ongoing mental and physical experience, this training leads to improved self regulation and can manifest as changes in mental states or as longer lasting traits (Cahn & Polich, 2006). Contemplative Neuroscience has been pioneered by individuals such as Francisco Varela, Richard Davidson, Daniel Goleman, Alan Wallace, Jon Kabat-Zinn and others, all of whom started to publish and speak publicly on these topics in the late 1970's and 80's. Research would suggest that contemplative practices not only offer insight into the scientific, phenomenological and philosophical understanding of the nature of consciousness, they equally shed light on the highly plastic neural circuitry underlying attention, emotion, sensory perception, and self-awareness.

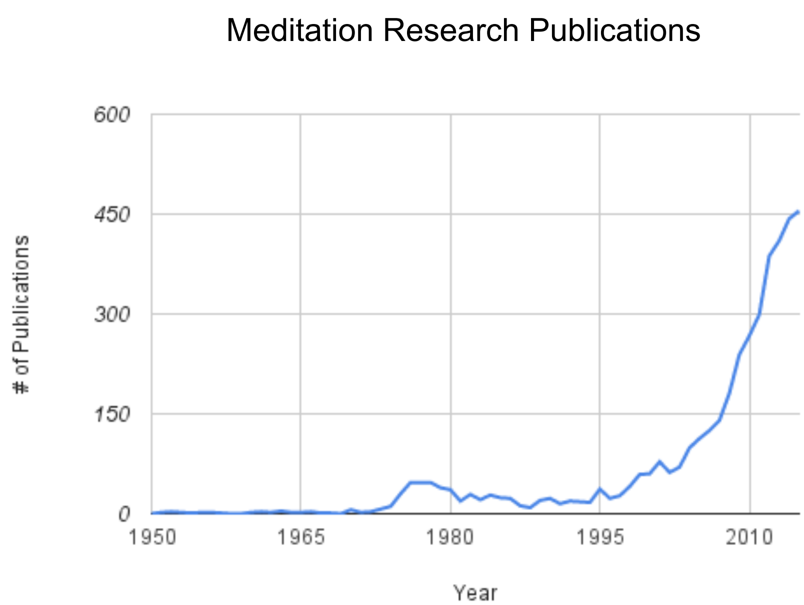
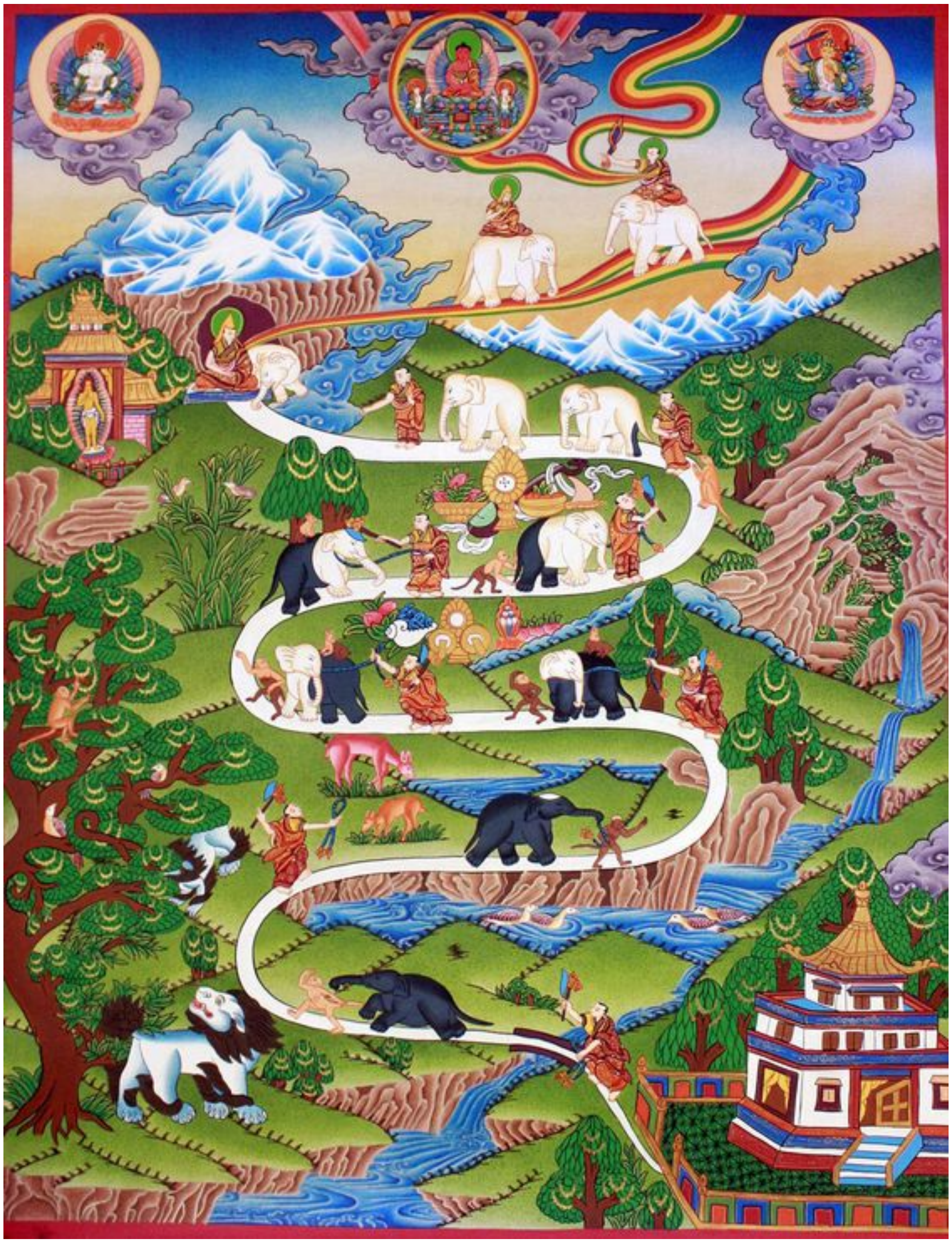


Figure 11. This figure shows the results of a pubmed search of Meditation Publications in the last 67 years.

In 1979, 35-year-old avid student of Buddhist meditation and MIT-trained molecular biologist Dr. Jon Kabat-Zinn launched his first study investigating the effects of mindfulness practices in a group of chronically ill patients who were nonresponsive to traditional medical treatments. According to Kabat-Zinn, mindfulness is the "awareness that arises through paying attention, on purpose, in the present moment, non-judgmentally...it's about knowing what is on your mind" (Baer, 2003). Having developed an eight-week protocol based on the fundamental teachings of Buddhist mindfulness, Kabat-Zinn has now brought the application of contemplative practices to tens of thousands of people, and into an enormous number of public, clinical and psychotherapeutic program settings through the development of Mindfulness Based Stress Reduction (MBSR; Baer, 2003; Grossman, Niemann, Schmidt, & Walach, 2004; J. Kabat-Zinn et al., 1998; Jon Kabat-Zinn, 2003). Mindfulness based interventions have been widely implemented in the treatment of anxiety and depression (Hofmann et al., 2010; Roemer et al., 2008, Salters-Pedneault, 2008), substance abuse (Bowen et al., 2006), and chronic pain (Grossman, Tiefenthaler-Gilmer, Raysz, & Kesper, 2007).

During a 1993 meeting between the Harvard neuroscientist Dr. Richard Davidson and the Dalai Lama, his Holiness asked Davidson why modern neuroscientific methods had been used to study emotions such as fear, anxiety and depression, but not kindness, openness and compassion. It was following these meetings that the research investigating contemplative practices started to surface in the broader mainstream neuroscientific community. Davidson and Kabat Zinn are pioneers who have paved the way for what many foresee as a new era reincorporating phenomenological experience into medical, clinical and fundamental scientific research. Almost a quarter of a century later, research on the effects of meditation has taken a prime seat in neuroscience and psychology research. This is in large part due to advancements in contemplative neuroscience that come from our rapidly evolving understanding of neuroplasticity; our brains are continuously changing in response to the environment, our experiences, and various forms of training. It is also becoming increasingly evidenced by a large body of literature that there is an ongoing bi-directional communication between mind/brain



Picture 1. The picture shows the path of a Buddhist monk as he makes steps on the path of meditation training from the beginning of the path starting at the bottom. The mind is represented as the elephant, and the distractions in life are depicted as a monkey, taunting him along the way. When faced by the challenges that the wandering mind presents, the monk later aids the elephant along the way. (Rubin At Foundation, himalyanan.org)

and body, implying that psychological well being is directly related to the physical health of both the body and the brain. While the exact mechanisms are not yet fully understood, research consistently demonstrates the downstream effects that occur in the body as brain circuits are transformed (Vitetta et al., 2005).

3.2 Classifying the different styles of Meditation

While mindfulness can be defined differently in contemporary contexts, as compared to traditional Buddhist contexts, it generally refers to a self-regulated attentional state focused on present-moment experiences, emphasizing curiosity, openness, and acceptance (Dahl, Lutz, & Davidson, 2015). While several core features are considered to be fundamental in meditative practice, much debate remains over various western translations, applications and constructs of mindfulness when compared to the more traditional Buddhist frameworks (Dahl et al., 2015). In a recent review by Dahl and colleagues (2015), three distinct classes or groupings of meditation styles that encompass a majority of the techniques and methods that are actively being researched have been proposed, and are discussed below. Functional frameworks such as these are essential for the accurate classification and segmentation of the accumulating research findings given the wide variety of practices and their corresponding neural mechanisms.

3.2.1 Forms of Attentional Meditation

Focused-attention (FA) practices are thought to cultivate enhanced concentration and single pointed focus on a given object in addition to the development of meta-awareness (Dahl et al., 2015; Lutz, Slagter, Dunne, & Davidson, 2008). The attentional and monitoring faculties that are cultivated in FA have been related to dissociable systems in the brain involved in conflict monitoring, selective and sustained attention (Manna et al., 2010). Open-monitoring (OM) practices similarly involve the cultivation of meta-awareness, but they do not involve selecting a specific object to orient one's attention to. Meta-awareness or metacognition refers to the increased awareness of the ongoing physical and self referential processes (Flavell, 1979). In these meditation practices, meditators attempt to expand their attentional scope to incorporate the flow of perceptions, thoughts, emotional content, and/or subjective awareness (Dahl et al., 2015; Lutz et al., 2008; Manna et al., 2010).

3.2.2 Deconstructive Meditation Practices

Deconstructive meditation practices are meditations practices that are thought to shed light on the interworking mechanisms of our ongoing experience. These practices include ‘object-oriented insight’, ‘subject-oriented insight’, and ‘non-dual-oriented insight’ forms of meditation (Dahl et al., 2015; Josipovic, 2013). These practices are thought to reduce one's sense of attachment or control removing the separation between the observer and the observed in order to achieve experiential insight into the true nature consciousness and to connect with a more unified reality underlying our daily experiences (Josipovic, 2013).

3.2.3 Constructive meditation practices

The constructive family of mediation practices primarily involves the generation and cultivation of compassion, traditionally using various mental imagery techniques, and is thought to shift self-referential cognitive, behavioral and affective patterns, toward tendencies and thoughts that involve the well-being of others (Dahl et al., 2015; Kang, Gray, & Dovidio, 2014). Whereas concentration and attentional forms of meditation emphasize the ongoing monitoring of mental content and placement of attention, constructive compassion meditation based practices aim at directly changing the content of thoughts and emotions (Dahl et al., 2015; Salzberg, 1997).

3.3 Neural Correlates of Meditation

3.3.1 Meditation, Neuroplasticity and Epigenetics

Scientific interest in the neurophysiological bases of meditation has in large part come from our understanding of neuroplasticity and various forms of experience-induced changes that occur in the brain (Lutz, Dunne, & Davidson, 2007). Contemplative Science research has shown that through the active and intentional shaping of our brains, we can promote and cultivate well-being and healthy habits by taking advantage of neuroplasticity. The regular practice of meditation has been shown to induce neuroplasticity not only in terms of brain functioning (Davidson & Lutz, 2008) but can induce changes in the physical structure as well (Hölzel, Carmody, et al., 2011). Sara W. Lazar and colleagues (2005) were the first to show that the prefrontal cortex and right anterior insula, regions associated with attention, interoception and sensory processing were thicker in experienced meditation participants than in matched controls. They also found that the between-group differences in prefrontal cortical thickness were most pronounced in older participants suggesting that meditation may slow age-related cortical thinning, and that the thickness of these two specific areas also correlated with meditation experience. Lazar and her colleagues provided some of the first structural evidence for experience-dependent cortical plasticity associated with meditation practice. Kang et al., (2013) conducted a whole-brain cortical thickness analysis based on magnetic resonance imaging, and diffusion tensor imaging to quantify white matter integrity in the brains of 46 experienced meditators compared with 46 matched meditation-naïve volunteers. They found significantly increased cortical thickness in the anterior regions of the brain, located in frontal and temporal areas, including the medial prefrontal cortex, superior frontal cortex, temporal pole and the middle and inferior temporal cortices in meditators as compared to controls. They additionally found that meditators had both higher fractional anisotropy values and greater cortical thickness in the region adjacent to the medial prefrontal cortex, suggesting structural changes in both gray and white matter (Kang et al., 2013).

Recent epigenetics research has shown that short term exposure to stress, diet and physical exercise can cause changes that are detectable in human peripheral tissues (Kaliman et al., 2011; Pham & Lee, 2012). In a study by Buchanan and colleagues (2012) elevated cortisol levels were found in individuals who scored high on empathy measures after observing stressful experiences in others, whereas observing stressful experiences in others while generating compassion was linked to reductions in cortisol levels (Cosley et al., 2010). These findings suggest that emotional qualities such as compassion and empathy can directly interact with the peripheral nervous system. Kaliman and colleagues (2014) explored the impact of a day of intensive practice of mindfulness meditation in experienced meditation practitioners on the expression of circadian, chromatin modulatory and inflammatory genes in peripheral blood mononuclear cells (PBMCs) and found a reduced expression of histone deacetylase genes (genes which play an important role in the regulation of gene expression) and a decreased expression of pro-inflammatory genes in meditators compared with controls. They suggest that the regulation of these genes and inflammatory pathways may represent some of the mechanisms underlying the therapeutic potential of mindfulness-based interventions.

Research investigating the effects of compassion training have found links between the duration of compassion training and inflammatory biomarkers, with an increased duration of compassion training leading to decreased levels of C-reactive protein and interleukin 6, both of which are biomarkers used to predict vascular risk (Pace et al., 2009, 2013). Jacobs and colleagues (2011) investigated the effects of a 3-month meditation retreat on changes in telomerase activity, which is considered to be a reliable predictor of long-term cellular viability (Epel et al., 2004). The study found that increases in perceived control and decreases in negative affect (which are central features targeted by the meditation practice) were correlated with increases in telomerase activity, telomere length and immune cell longevity (T. L. Jacobs et al., 2011). These findings suggest that through various meditation practices we can change the way our minds and bodies react to stressful events in the environment, and that these changes directly impact our peripheral biology.

3.3.2 Meditation and Oscillations

The phenomenological differences associated with meditation practice suggest that these various meditative states (those that involve focus on an object and those that are objectless), as well as meditation traits may be associated with very different EEG oscillatory signatures (Cahn & Polich, 2006). A number of reports have suggested that increased theta (4 – 8 Hz) rather than increases in alpha power during meditation may be a specific state effect of meditative practice (Aftanas & Golocheikine, 2001, 2002; Corby, Roth, Zarcone, & Kopell, 1978; Elson, Hauri, & Cunis, 1977; Fenwick et al., 1977; Hebert & Lehmann, 1977; Jacobs & Lubar, 1989; Fred

Travis, Tecce, Arenander, & Wallace, 2002; Warrenburg, Pagano, Woods, & Hlastala, 1980; Pagano & Warrenburg, 1983; Anand, Chhina, & Singh, 1961; Banquet, 1973, Hirai, 1974). Some studies of yogic meditative practice found increases in theta to be associated with proficiency in meditative technique (Aftanas & Golocheikine, 2001; Corby et al., 1978; Elson et al., 1977; Kasamatsu & Hirai, 1966), and early investigations with Zen meditation indicate theta increases to be characteristic of only the more advanced practitioners (Kasamatsu & Hirai, 1966). While increased frontal midline theta has been observed during meditation (Aftanas & Golocheikine, 2002; Hebert & Lehmann, 1977; Kubota et al., 2001), similar frontal midline activations occur in non-meditation-related studies of sustained attention and memory (Jensen & Lisman, 2001; Scheeringa et al., 2009).

In the early 1970's, some of the first biofeedback studies discovered that global increases in alpha activity seem to correlate with reductions in anxiety, and increased feelings of calm and positive affect (Brown, 1970; Hardt & Kamiya, 1978; Kamiya, 1969). Following the discovery that alpha rhythm modulation is correlated with sensory filtering during body-sensation focused attention, Kerr et al. (2013) found that subjects trained in mindfulness showed enhanced top-down modulation of a localized alpha rhythm in somatosensory cortices. Increased intra- and inter-hemispheric alpha–theta range coherence has also been observed during meditation (Aftanas & Golocheikine, 2001, 2002; Anand et al., 1961; Banquet, 1973; Faber, Lehmann, Gianotti, Kaelin, & Pascual-Marqui, 2004; Farrow & Hebert, 1982; Gaylord, Orme-Johnson, & Travis, 1989; Pagano & Warrenburg, 1983; Travis & Pearson, 1999; F. Travis, 2001; F. Travis & Wallace, 1999; Hebert & Tan, 2004), while similar effects were found in long-term meditators at rest or while engaged in cognitive tasks (Dillbeck & Vesely, 1986; Orme-Johnson & Haynes, 1981, Hebert & Tan 2004).

In a study by Lutz et al. (2004), long-distance phase-synchronized gamma-band oscillations were observed when meditators practiced a non-referential form of compassion meditation when compared to a control group. The authors emphasize in their article that according to the first-person accounts of 'objectless meditation', the methods and states that occur during this meditation differ radically from those of concentration meditation, lacking specific objects and with the focus on the cultivation of a particular state of being. Given the large amplitude of the gamma oscillations in Lutz et al. (2004), the authors conclude that the size and scale of the oscillating neural population reflected the activity of widely distributed neural assemblies that were synchronized with a high temporal precision. Differences between the control and the meditation populations during the resting state before meditation were also observed, suggesting that the differences between neural activity during formal seated meditation practice and everyday life is reduced in advanced practitioners and that the resting state of the brain may be altered by long-term meditative practice.

3.4 Meditation and its effect on cognition

3.4.1 Meditation and Attention

One of the key findings from contemplative neuroscience research relates to its mediating role on the neural mechanisms underlying top down feedback mechanisms involved in attention regulation and sensory perception. According to the neurocognitive model developed by Posner and Petersen (1990), attention can be divided into three different anatomically and functionally distinct networks that implement the functions of alerting (which refer to the anticipatory preparation for an incoming stimulus), orienting (the directing of attention to a specific stimulus), and conflict monitoring and executive attention (resolving conflict between competing neural activity) (Figure 12; Posner and Petersen, 1990; Posner, Rueda and Kanske 2007). Additional distinctions between different forms of attention refer to combinations of these three components (Posner and Petersen, 1990). For example, sustained attention refers to the sense of vigilance during long continued tasks and may involve both tonic alerting and orienting, whereas selective attention may involve either orienting (when a stimulus is present) or executive function (when stored information is involved; Desimone & Duncan, 1995).

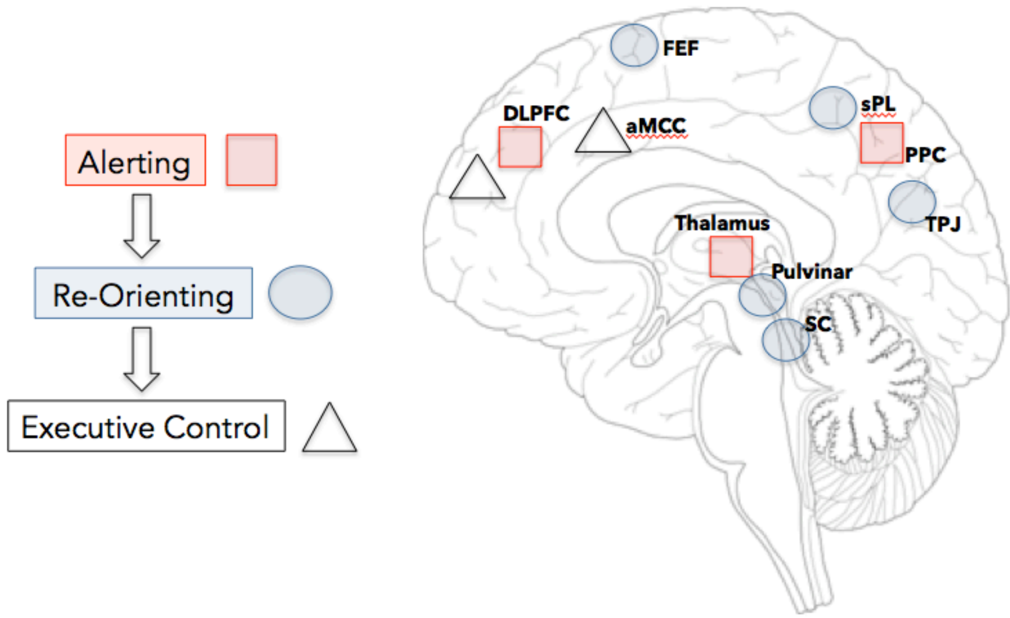


Figure 12. The main hubs associated with the alerting, orienting and executive attention networks Adapted from Posner & Rothbart (2007)

A study by Slagter and colleagues (2007) demonstrated that three months of focused meditation training resulted in a smaller attentional blink and reduced brain-resource allocation to the first target (T1), demonstrated by a significantly smaller T1-elicited P3b, a neural index of resource allocation after training. Subjects with the largest decrease in cognitive resource allocation to T1 showed the largest reduction in the measured attentional-blink size, suggesting that the ability to accurately identify T2 depends upon the efficient deployment of cognitive resources to T1. They hypothesized that increases in phase locking were induced via mental training and the subjects enhanced capacity to sustain task-related attentional focus, while reducing the tendency to engage in task-unrelated thoughts. These findings suggest that through meditation practices one can improve cognitive capacity, potentially via the self-regulation of lower level elements of neurogenesis (Vago & Silbersweig, 2012), and demonstrate that mental training can result in increased control over the distribution of limited brain resources (Slagter et al., 2007).

There have been a considerable number of studies that have associated the practice of mindfulness meditation with improvements in attention (Brefczynski-Lewis, Lutz, Schaefer, Levinson, & Davidson, 2007; Chan & Woollacott, 2007; Jha, Krompinger, & Baime, 2007; Lutz et al., 2009; MacLean et al., 2010; Moore & Malinowski, 2009; Slagter et al., 2007; Valentine & Sweet, 1999; van den Hurk, Giommi, Gielen, Speckens, & Barendregt, 2010). For instance, in the studies by Moore and Malinowski (2009) and Chan and Woollacott (2007), reduced effects of distracting, conflicting information were found in the Stroop task. In a study by van den Hurk et al. (2010) mindfulness meditators showed reduced interference by distracting flankers in the attention network test. The practice of mindfulness meditation has been related to more flexible orienting of attention by a reduction in the time needed to shift attention from one location to another (Hodgins & Adair, 2010; Jha et al., 2007; van den Hurk et al., 2010). In a study comparing open monitoring meditation (OM), focused attention meditation (FA) and a relaxation group on performance on an emotional variant of the Attention Network Test (ANT), OM and FA practice improved executive attention, with no change observed in the relaxation control group. These findings suggest that mindfulness meditation may target some of the executive attention mechanisms contributing to or underlying mood and anxiety disorders (Ainsworth, Eddershaw, Meron, Baldwin, & Garner, 2013).

A number of structural and functional MRI studies on mindfulness training have investigated the neuroplasticity in brain regions supporting attention regulation. The anterior cingulate cortex (ACC) is an area in the brain that has been most consistently linked to the effects of mindfulness training on attention (Tang et al., 2009, 2010; Tang, Rothbart, & Posner, 2012; Tang, Tang, & Posner, 2013; Tang & Posner, 2014; Hozel et al., 2007), however, other regions including the insula, temporo-parietal junction, fronto-limbic network, and other structures associated with the default mode network have been consistently identified with extensive meditation practice (Fox et al., 2012). The ACC and the fronto-insular cortex are thought to enable executive attention and control (Van Veen & Carter, 2002) by detecting the presence of conflicts emerging from incompatible streams of information processing, thus facilitating cognitive processing through long-range connections to other brain areas. These mechanisms may work synergistically by establishing a process of enhanced meta-awareness and self-regulation following long-term meditation practice (Fox et al., 2012; Tang et al., 2015).

3.4.2 Meditation and Emotion

Well-being is a complex phenomenon that is related to a variety of factors, including cultural differences, socioeconomic status, health, the quality of interpersonal relations, and specific psychological processes (Dinero et al., 2011). Clinical research suggests that an ability to distance oneself and observe the ongoing internal train of thoughts plays a vital role in psychological well-being (Farb et al., 2007). Within the domain of cognitive psychology, it is thought that latent conceptions of self underlie to a great extent our thoughts and emotions and directly impact brain functioning (Hoffman et al., 2012). It is thought that one of the primary mechanisms by which contemplative practices affect well-being is by targeting and altering maladaptive self-referential patterns of thought (Dahl et al., 2015).

These findings are backed by additional research studying the neural mechanisms underlying the regulation of emotion which have been directly linked to brain regions associated with cognitive control, including the dorsomedial, dorsolateral, and ventrolateral prefrontal cortex, as well as the posterior parietal cortex (Figure 13; Kohn et al., 2013; Ochsner & Gross, 2005; Ochsner et al., 2004). It may be that meditation and mindfulness mediate emotion regulation by strengthening prefrontal cognitive control mechanisms via suppression of activity in the amygdala. Diminished activations in the amygdala in response to emotional stimuli were found in meditation practitioners (Tang et al., 2015). Furthermore, Weng et al. (2013) found that participants who were trained in compassion based meditation showed increased connectivity in response to emotionally provocative images between the dorsolateral prefrontal cortex (a region commonly linked to cognitive functions, such as reappraisal) and the nucleus accumbens, considered to be a key hub in the reward network associated with positive affect. According to a review by (Hölzel, Carmody, et al., 2011), the key factors in emotion regulation involve reappraisal, exposure, extinction and reconsolidation. Hanley & Garland (2014) found that mindfulness practice leads to increases in positive reappraisal. They argue that mindfulness

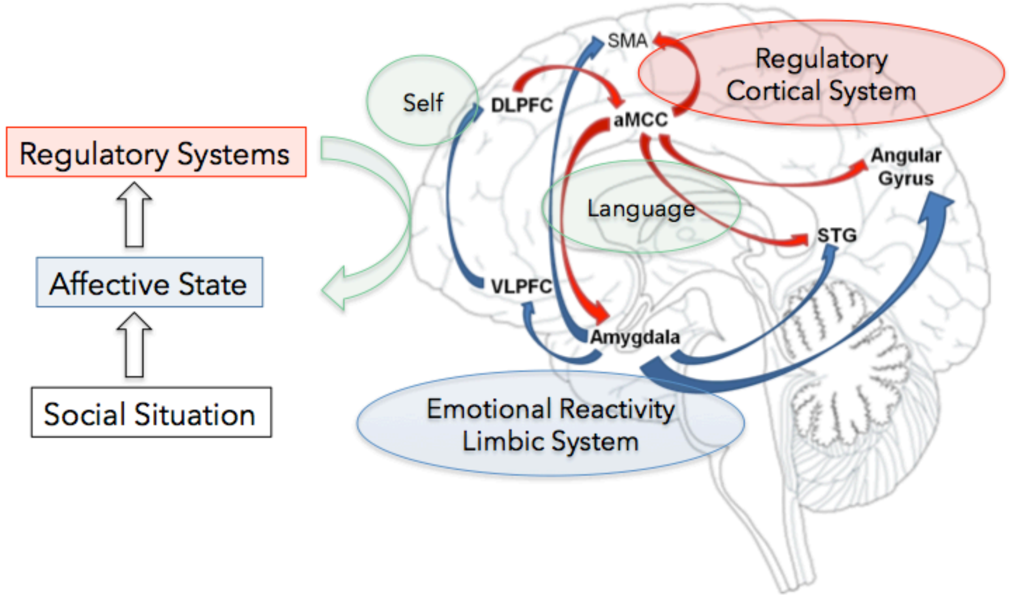


Figure 13. Proposed in Kohn et al (2013), the superior temporal gyrus, angular gyrus and (pre) supplementary motor area are involved in execution of regulation initiated by frontal areas. The dorsolateral prefrontal cortex may be related to regulation of cognitive processes such as attention, while the ventrolateral prefrontal cortex may not necessarily reflect the regulatory process per se, but signals salience and therefore the need to regulate. The anterior middle cingulate cortex was identified as a region, which is anatomically and functionally in an ideal position to influence behavior and subcortical structures related to affect generation and are theorized to play a central, integrative role in emotion regulation.

practices facilitate "positive reappraisal," with reappraisal functioning as an adaptive process through which stressful events are reconstructed as beneficial, meaningful, or benign. Research findings suggest that there are notable similarities in the brain regions being influenced by mindfulness meditation and those involved in mediating fear extinction, namely the hippocampus, amygdala, medial PFC, and the ventromedial PFC (Goldin & Gross, 2010; Hölzel et al., 2008; S. W. Lazar et al., 2000). According to Hölzel and colleagues (2011) during mindfulness meditation, one allows themselves to be affected by the experience, while refraining from engaging in internal reactivity toward it, while cultivating acceptance to bodily and affective responses. These findings suggest that meditation practice may help to facilitate enhanced awareness and reduced reactivity to the content of our ongoing internal dialogue.

Chapter 4: Meditation and Neurofeedback

This chapter was published in a special edition of Frontiers in Consciousness Research (Brandmeyer and Delorme, 2013). The review article highlights; a) the need for further studies on specific contemplative traditions to illuminate distinct neural features that are consistent with specific aspects of meditation states and traditions (addressed in experiment 1), and b) discusses the need for research studies to test whether these types of 'neural signatures' of meditative features could be developed into various types of neurofeedback protocols that could used by the general public to facilitate learning meditation techniques (addressed in experiment 2).

4.1 Meditation and Neurofeedback

Dating back as far as 1957, the academic investigation of meditation and the Asian contemplative traditions has fascinated not only the likes of philosophers and religious scholars, but researchers in the fields of neuroscience, psychology and medicine. While most of the contemplative traditions are comprised of spiritual practices that aim to bring the practitioner closer to self-actualization and enlightenment, from a neuroscientific and clinical perspective meditation is usually considered as a set of diverse and specific methods of distinct attentional engagement (Cahn & Polich, 2009).

Over the last decade, we have witnessed an exponential increase in the interest in meditation research. While this is in part due to improvements in neuroimaging methods, it is also due to the variety of medical practices incorporating meditation into therapeutic protocols. With the general aim of understanding how meditation affects the mind, brain, body and general health, particularly interesting findings in recent research suggest that mental activity involved in meditation practices can induce brain plasticity (Lazar et al., 2005; Lutz et al., 2004).

With its increasing popularity, many people in Western societies express an interest and motivation to meditate. However, for many it can often be quite difficult to maintain a disciplined and or regular practice, for reasons ranging from a lack of time to general laziness. It is possible that machine assisted programs such as neurofeedback protocols for mobile applications may help individuals develop their meditation practice more rapidly. Methods such as neurofeedback incorporate real-time feedback of electro-encephalography (EEG) activity to teach self-regulation, and may be potentially used as an aid for meditation.

While Neurofeedback and Biofeedback have been used since the 1960s, previous neuroscientific and clinical research investigating its efficacy has been limited lacking controlled studies and significant findings (Moriyama et al., 2012). However a recent overview of the existing body of literature on neurofeedback research has now led the American Academy of Pediatrics to recognize neurofeedback and working memory training as some of the most clinically efficacious treatments for children and adolescents with attention deficit and hyperactivity disorders (ADHD; Dename 2003). Neurofeedback has been used to treat a wide variety of other disorders such as insomnia, anxiety, depression, epilepsy, brain damage from stroke, addiction, autism, Tourette's syndrome, and more (Coben, Linden, & Myers, 2010; Cortoos, De Valck, Arns, Breteler, & Cluydts, 2010; Messerotti Benvenuti, Buodo, Leone, & Palomba, 2011; Mihara et al., 2013; Tan et al., 2009). As with all therapeutic interventions it is important to note that individuals who are seeking neurofeedback for diagnostics or for clinical and medical purposes seek qualified and licensed practitioners, as adverse effects of inappropriate training have been documented (Hammond & Kirk, 2008).

Interestingly, many of the conditions that benefit from neurofeedback treatment are consistent with the conditions that improve with regular meditation practice. For example, both ADHD patients and individuals diagnosed with depression benefit from meditation training (Grant et al., 2013; Hofmann et al., 2010) as well as neurofeedback training protocols (Arns, de Ridder, Strehl, Breteler, & Coenen, 2009; Peeters, Ronner, Bodar, van Os, & Lousberg, 2014). In addition, both meditation and neurofeedback are methods of training mental states. Thus it is plausible that the mental training involved in meditation may be fundamentally no different than other types of training and skill acquisition that can induce plastic changes in the brain (Sara W. Lazar et al., 2005; Pagnoni & Cekic, 2007).

One hypothesis to explain the similarity between meditation and neurofeedback is that both techniques facilitate and improve concentration and emotion regulation, for which both attentional control and cognitive control are necessary. When one aims to alter attentional control one must learn to manipulate the amount of attention that is naturally allocated to processing emotional stimuli. Similarly, when an individual is attempting to exercise or gain some form of cognitive control they must alter their expectations and judgments regarding emotional stimuli (Braboszcz, Hahusseau, & Delorme, 2010; Josipovic, 2010). These core principles are central to both meditation and neurofeedback, with the distinguishing feature being that meditation is self-regulated, and neurofeedback is machine aided. It is worth noting that the alpha and theta frequency bands trained in most cognitive enhancement neurofeedback protocols (Zoefel, Huster, & Herrmann, 2011) share many similarities with the EEG frequency bands that show the most significant change during the early stages of meditation practice (Braboszcz & Delorme, 2011; Cahn, Delorme, & Polich, 2013).

The integration of meditation and neurofeedback has already happened in popular culture. Numerous neurofeedback companies already provide so called 'enlightenment' programs to the public. The programs developed by these companies however, are not all based on the scientific study of meditation and or neurofeedback and the reliability and accuracy of signal detection in many of the portable devices currently on the market remains questionable. While many of these companies are relying on the intuitions of their founders for various neurofeedback protocols, it is necessary for these programs to adopt a more rigorous scientific approach, such as those developed for patients being treated using neurofeedback (Arns et al., 2009). More research is required to refine the methods, devices, techniques and protocols that are most effective within a normal population.

Assuming that reliable and reproducible EEG signatures are associated with specific meditation practices, we may expect that training subjects to reproduce these signatures would support and strengthen their meditation practice. Clinical neurofeedback protocols are aiming towards comparing patients' EEG with large EEG data sets from normal subjects in order to produce a neurofeedback algorithm that rewards patients whose EEG becomes closer to that of the normal population (Thornton & Carmody, 2009). Similarly, it might be possible to train users to make their EEG brain waves similar to the brain waves of an expert meditation practitioner in a given tradition. We do not argue that the task of the user should be only to up-regulate or down regulate their EEG, instead they would perform a meditation practice and the neurofeedback device would act in the periphery, providing users with feedback on how well they are doing. For this to be feasible there needs to be a clear identification of the EEG neural correlates of specific meditation techniques and traditions. As evidenced in the literature, there are an abundant number of meditation traditions and styles, many which have vastly differing techniques, methods and practices. As the mental states associated with particular meditations differ, so does the corresponding neurophysiological activity (Cahn & Polich, 2006). Recent research suggests that complex brain activity during meditation may not be adequately described by basic EEG analyses (Fred Travis & Shear, 2010). Thus, more research and the use of more advanced signal processing tools are needed in order to understand the differences in meditative techniques, and to better define a normative population which EEG brainwaves could be used in a neurofeedback protocol.

Another type of neurofeedback program could help detect mind wandering episodes. In all of the meditation traditions, practitioners often see their attention drifting spontaneously towards self-centered matters. These attentional drifts are termed mind wandering, and have recently been focused on in neuroscientific research (Braboszcz & Delorme, 2011). Braboszcz and Delorme (2011) observed clear changes in the alpha and theta frequency bands during mind wandering as compared to a breath focus task. A neurofeedback device could provide an alarm to users when their mind starts to wander, therefore supporting and improving upon their meditation practice. Although future research should assess the reliability of these measures to detect single mind wandering episodes, such a neurofeedback system might help support users in their meditation.

Most neurofeedback systems provide auditory or visual feedback that fully engage and demand the attention of the subject. For neurofeedback-assisted meditation, the goal would be to provide subtle cues that do not disturb the subjects' meditation. For example, white noise could be made louder as the subjects EEG departs from the EEG of the normative population of meditators. Similarly, the same white noise amplitude could also reflect the likelihood of the subject's mind wandering. As mentioned earlier, the neurofeedback device would not be a substitute to meditation practice, but rather a means to facilitate and support it in its early to middle states of practice.

Over the last century, and ever more so at present, machines have become extensively integrated into a vast range of human activity. The practice of meditation requires sustained attention that is often hard to achieve for novices, as compared to more advanced practitioners (Brefczynski-Lewis et al., 2007). Therefore an inspiring application of machine-aided learning may be to help offer alternatives for beginners who struggle with maintaining a regular meditation practice. Learning how to meditate faster and more easily may facilitate access to meditation techniques to a wider audience. Still, it may also be beneficial for more experienced meditators who are interested in deepening their meditation practices. Even the Dalai Lama has publicly stated that he would be the first to use this type of technology, and believes that neuroscience will improve Buddhist practices (Mind and Life Dialogues, 2004).

This type of application also has the potential of reaching the masses as meditation and neurofeedback could be integrated into the domain of smartphones and apps (Szu et al., 2013). In fact, some EEG systems are already compatible with portable and smartphone technology, and it will not be long before we start seeing neurofeedback-based programs for smartphones. Community building over social media using cloud based computing could help users support one another and their meditation practices. In addition to supporting meditation practice, such neurofeedback applications can help track the progress of users over weeks and years and assess changes that users may not be consciously aware of, thus encouraging users to pursue their practice. Using neurofeedback to learn meditation truly reflects new, cutting edge science, and via real-time feedback we may be able to develop a precise ways to rapidly learn and achieve deeper states of meditation.

In conclusion, it is our belief that mobile neurofeedback systems and protocols that are derived and extend upon meditative traditions and practices offer a promising new direction and platform in mobile technology. These technologies would be not only for people who have taken interest in these kinds of practices or people who have already established themselves in a meditative practice, but for people who are looking for new methods to train, improve and develop attention and emotion regulation. We want to emphasize that while these devices may aid and assist individuals in their meditation practice, the goal of these practices is ultimately the decrease of reliance on objects and external constructs for support. This type of research should also integrate neurophenomenological approaches that take into account first-person reports of subjective experience in conjunction with the experimental investigation of brain activity (Braboszcz et al., 2010; Josipovic, 2010). Real-time feedback of brain activity as implemented in neurofeedback may help develop new frameworks for the scientific investigation of embodied consciousness and the interactions between mind and body.

Part II

Chapter 5: EEG study of Mind Wandering in Meditation Practitioners

5.1 Introduction

An intriguing finding emerging from the field of contemplative neuroscience involves the mediating role of contemplative and meditative practices on the neural mechanisms underlying top-down regulation of sustained attention and sensory perception. An electroencephalography (EEG) study by Braboszcz and Delorme (2011) showed enhanced cortical processing of sensory stimuli during a sustained breath awareness task when compared to periods of time in which subjects reported mind wandering. Known as the perceptual decoupling hypothesis, the processing of sensory information during periods of mind wandering is more superficial (Schooler et al., 2011). Mrazek et al. (2013) found that after two weeks of mindfulness meditation training, participants who were initially most prone to distraction showed improved verbal Graduate Record Examination (GRE) scores after meditation training in addition to enhanced working memory capacity as measured by a working memory task. These changes were directly mediated by reduced mind wandering as measured by experience sampling using both probe-caught and self-reported mind wandering episodes during both the GRE and working memory tasks. In another study by Mrazek, Smallwood, & Schooler (2012), eight minutes of mindful breathing attenuated indirect performance markers of mind wandering during a sustained attention task. In a set of studies by Zanesco et al. (2016) exploring the effects of intense meditation training on mind wandering, two separate groups of participants who took part in either a one month insight meditation retreat, or a three month shamata meditation retreat, showed a reduced tendency of the mind to wander as measured by reduced mindless reading and reduced probe-caught mind wandering measured during a reading task requiring ongoing error monitoring.

Arguably the cornerstones of most contemplative practices include the training and development of sustained attention (Slagter et al., 2007), the flexible monitoring of sensory experience (Kerr et al., 2011; Tang et al., 2015) and the cultivation of metacognitive awareness via active monitoring of mental states (Baird, Mrazek, Phillips, & Schooler, 2014). Taken together, these faculties may facilitate increased efficiency in the distribution of our limited cognitive resources (Global workspace theory; Baars et al., 2005). Increased functional connectivity in networks associated with both attention and executive functioning (Hasenkamp & Barsalou, 2012; Teppers & Inzlicht, 2013) have been observed in advanced meditation practitioners, in addition to the aforementioned findings in the DMN (Jang et al., 2011). Given the large body of literature showing reduced DMN activations in advanced practitioners, and that meditation leads to reduced DMN processing beyond that observed during other types of cognitive tasks (Garrison, Zeffiro, Scheinost, Constable, & Brewer, 2015), these findings may suggest that increased functional connectivity may reduce BOLD activity, reflecting an efficient use of cognitive resources (Baars et al., 2005). Contrary to these findings, a recent study by Berkovich-Ohana et al. (2016) found reductions in functional connectivity in experienced meditators. Therefore more research is needed to clarify the neurophysiological implications of functional connectivity in meditation practice and beyond.

In a study using magnetoencephalographic (MEG) recording of the somatosensory cortex finger representation, Kerr et al. (2011) found that experienced meditators showed an enhanced alpha power modulation in response to a cue, potentially reflecting an enhanced filtering of inputs to primary sensory cortex. They also found that experienced meditators demonstrated modified alpha rhythm properties and an increase in non-localized tonic alpha power when compared to controls. These findings can most likely be attributed to the emphasis on somatic attention training in mindfulness meditation techniques in which individuals train to develop metacognition; a process in which one directs their attention, moment-by-moment, to an overall somatosensory awareness of physical sensations, feelings, and thoughts (Cahn & Polich, 2006; Segal, Teasdale, & Mark, 2004). Whitmarsh et al. (2014) investigated participant's metacognitive ability to report on their attentional focus, and found that contralateral somatosensory alpha power decrease correlated with higher reported attentional focus to either their left or right hand respectively. Baird, Mrazek, et al. (2014) found that a 2-week meditation program led to significantly enhanced metacognitive ability for memory, but not for perceptual decisions, suggesting that while meditation training can enhance certain elements of introspective acuity, such improvements may not apply equally to all cognitive domains. Enhanced body awareness was also found to be associated with greater subjective emotional experience and awareness of the heart during exposure to emotionally provocative stimuli in Vipassana meditators, when compared to expert dancers, and controls (Sze, Gyurak, Yuan, & Levenson, 2010). Given that top-down attentional modulations of cortical excitability have been repeatedly shown to result in better discrimination and performance accuracy, the aforementioned findings provide support for both the enhancement of metacognitive accuracy via the direct monitoring of current mental states resulting from long term meditation practice, and for possible changes in the supporting neural structures underlying sustained attention processes.

One outstanding question in the contemplative science literature relates to the direct impact of meditation experience on the monitoring of mind wandering and the degree to which practice influences the meta-cognitive awareness, duration and frequency of mind wandering events. In order to extend our scientific understanding of these temporally fluctuating mental states and phenomena in experimental settings, and given that subjects are generally unaware of mind wandering at the moment it occurs, the direct measurement challenge this poses for identifying the underlying mechanisms involved in attentional lapses requires nuanced neuroimaging methodology. Thus, we designed a novel paradigm based on experience sampling probe presentations to gain insight into the dynamic measures of EEG by comparing the degree (subjects responded on a scale from 0-3) of self-reported absorption experienced during meditation with the self-reported absorption experienced during mind wandering. To assess the relation between mind wandering and meditation, we tested 2 groups of meditators, one with a moderate level of experience and one with an advanced practice level. The central question in this investigation was to test if the level of meditation proficiency enhances the capacity for sustained attention, the awareness of and accuracy of self-report, and the metacognitive labeling of mental states. Our goal was also to contrast the neural dynamics of mind wandering and meditation, as well as an overall correlation between the EEG data and the first person behavioral data in this context.

5.2 Methods and materials

5.2.1 Participants

The study was conducted at the Meditation Research Institute (MRI) in Rishikesh, India. Twenty-five meditators from the Himalayan Yoga tradition participated in this study and were assigned to one of two groups based on experience and hours of daily practice. After data collection, one participant reported that they did not fully understand the task instructions and was excluded from the analyses, therefore Twenty-four participants were included in the analyses. Individuals who had engaged in a daily meditation practice for a minimum of 2 hours daily, for 1 year or longer were considered expert practitioners (N=12; mean hours weekly=14.8, SD= 1.6 hours; mean age= 39.3, SD= 12.0). Participants who were trained and familiar with the techniques, but who reported irregular practice (N=12; mean hours weekly= 3.2, SD= 3.1 hours; mean age= 45.0, SD= 14.8) were considered non-expert practitioners. All participants provided written consent to participate in the study and completed an extensive list of questions regarding their meditation background. Participants stated that they were not taking any medications that could potentially affect their concentration. The study received ethical approval from both the ethics committee of the Meditation Research Institute in India, and from the *Comité de Protection des Personnes* in France. Participants were all volunteers and were not compensated.

5.2.2 Experimental paradigm and Procedure

All participants were asked to meditate continuously throughout the experiment in their usual seated meditation position (either seated on the floor, or in a chair). Meditators were all practitioners of the Himalayan Yoga tradition. Once subjects were comfortably seated in their meditative posture, they were instructed to begin their meditation. All practitioners began with an initial body scan as they relaxed into their seated posture, and then started to mentally recite their mantra. Mantras are traditionally a word or sentence assigned to them by their meditation teacher. When deeper levels of meditation or stillness are obtained mantra repetitions gradually cease. Mantras are derived from Sanskrit root words and syllables, whose resonance is thought to induce stability of the mind without the need for an overly intense focus.

Experience sampling probes were presented at random intervals ranging from 30 seconds to 90 seconds throughout the duration of the experiment. Probes, in the form of pre-recorded vocalized questions, were presented on two freestanding speakers, and were reported as clearly audible by all subjects. Each experience sampling probe series consisted of three questions, which were presented in the same order throughout the experiment and are described in detail below. Subjects responded on a small, customized numeric USB keypad resting on their right thigh, to enable their right hand to comfortably rest without having to move or open their eyes. The time range of the experiment lasted from 45 minutes to 1 hour 30 minutes, as some subjects were willing and able to sit comfortably for longer periods of time. The average number of probes that participants received was 30. The entire experiment was programed and automated using the Matlab psychophysics toolbox. All participants completed a 5-minute training block prior to performing the experiment.

Experience sampling probes consisted of three questions that followed sequentially (Figure 14); the first question was Q1: “Please rate the depth of your meditation”, for which participants evaluated the subjective depth of their ‘*meditative state*’ for the moments immediately preceding the first probe, on a scale from 0 (not meditating at all) to 3 (deep meditative state) by pressing the corresponding key on the keypad. After their response was registered, the second question Q2: “Please rate the depth of your mind wandering” automatically followed. Participants evaluated the subjective depth of their ‘*mind wandering*’ for the period of time which immediately preceded the first probe, on a scale from 0 (not mind wandering at all) to 3 (immersed in their thoughts). The last question was Q3: “Please rate how tired you are”, where participants were asked to rate the subjective depth of their drowsiness before the first question, from 0 (not drowsy at all) to 3 (very drowsy). All responses pertained to the evaluations of the same time period immediately preceding the first probe. Participants were then instructed to resume their meditation with the prompt: "You may now resume your meditation".

Figure 14. Timeline of Experimental design. Pseudo Random probes (randomly interspaced between 30 and 90 seconds) prompted subjects to respond via key press by subjectively evaluating the depth of their experience on a scale from 0-3 to three questions: Q1 for "Please rate the depth of your meditation"; Q2 for "Please rate the depth of your mind wandering"; Q3 for "Please rate how tired you are". The letter R on the timeline corresponds to the instruction "You may now resume your meditation".

5.2.3 Data acquisition

We collected data using a 64 channels Biosemi system and a Biosemi 10-20 head cap montage at 2048 Hz sampling rate. Respiration, heart rate (ECG/HRV) and galvanic skin response (GSR) were also recorded, but results from this data will not be reported here.

Data processing was done using Matlab (The Mathworks, Inc.) and EEGLAB software (Delorme & Makeig, 2004). The raw EEG data was average referenced and down-sampled to 256 Hz. A high-pass filter at 2 Hz using an infinite impulse response filter (IIR; transition bandwidth of 0.7 Hz and order of 6) was applied, and the data was then average referenced again. The high pass filter was necessary to obtain high quality ICA decompositions on some subjects (see below) and, even though it was not necessary for all subjects, we opted to use the same high pass filter settings for all subjects to ensure that all data were processed uniformly. Data were then segmented into 10 second-epochs, ranging from -10.05 seconds to -.05 seconds prior to the onset of question Q1 in the experience sampling probe series. Bad electrodes (0 to 20 per subject, average of 6 per subject) and bad epochs containing paroxysmal activity were manually removed. Extended Infomax Independent Component Analysis (ICA) was then used to identify ocular and muscle artifacts (Delorme, Sejnowski, & Makeig, 2007). ICA components for eye blink, lateral eye movements and temporal muscle noise were identified and subtracted from the data by the visual inspection of both the component scalp topographies and power spectrum distributions. Between 1 and 5 artifactual components were removed for each subject. After artifact rejection, between 21 to 64 clean data epochs (mean of 38.1; SD of 12.6) were included in subsequent analyses for each subject.

5.2.4 EEG Time Frequency Analysis and Statistics

We applied a Welch-like analysis on the 10s long epochs (Welch, 1967). The difference with the Welch method is the implementation of wavelets instead of the fast fourier transform (FFT). We used a Morlet wavelet decomposition with 200 linearly-spaced time windows and a series of 100 log-spaced frequencies that range from 1 to 128 Hz. The wavelet used to measure the amount of data in each successive, overlapping time window has a 3-cycle wavelet at the lowest frequency. The number of cycles in the wavelets used for higher frequencies increase linearly, reaching 60 cycles at its highest frequency of 128 Hz. Parametric statistics for behavioral results were performed in Excel, Statistica, and Matlab using paired t-test, unpaired t-test with unpooled variance estimates, and linear regression. For EEG data, statistics were conducted on topographic and time-frequency maps using two-tailed paired or unpaired statistics. For the EEG data, correction for multiple comparisons was performed using the cluster method developed by Maris & Oostenveld (2007), which is based on a non-parametric Monte-Carlo permutation method. Channel topographies for this clustering method were established by setting the number of channel neighbors to 4.5 (Maris & Oostenveld, 2007). We also used False Discovery Rate (Benjamini & Yekutieli, 2001) to correct for multiple comparisons and obtained similar results as compared to the cluster method.

5.2.4.1 Behavioral Results

Expert practitioners reported a significantly lower depth of mind wandering than non-expert practitioners (mean 1.14 vs 1.59; with parametric unpaired two-tailed t-test with correction for non-homogeneous variance $p=0.03$; with permutation statistics and 20000 permutations $p=0.03$).

Expert practitioners also reported a greater depth of meditation than non-experts, although this effect failed to reach significance (mean 1.85 vs 1.39; degree of freedom (df) of 11; with parametric statistics p=0.06; with permutation statistics p=0.06). When taking the rating difference between the two questions (Q1 minus Q2), the difference between expert and non-expert practitioners was even larger (mean -0.20 vs 0.71; with parametric statistics p=0.0084; with permutation statistics p=0.0088). There was no difference in terms of alertness between expert and non-expert participants and all participants were relatively alert as reflected by the low tiredness ratings (mean 0.69 vs 0.73; ns with both parametric and permutation statistics). No significant correlations were observed between meditation and mind wandering (r^2=0.05; ns) or between meditation depth and drowsiness (r^2=0.02; ns) when all participants were pooled together. When considering the two groups of participants, such correlation was again low and not significant. However, a strong positive correlation was observed between mind wandering and drowsiness across all participants (r^2=0.31; p=0.004), with positive correlations observed for both groups of subjects, and reaching significance for expert practitioners (r^2=0.66; p=0.0013) but not for non-expert practitioners (r^2=0.2; ns). Average subject responses are summarized in Table 1. To test if responses to probes changed over time, we compared the behavioral responses for the first 20 probes, comprising at least 75% of the subjects (probes were delivered at random intervals, thus subjects received a varying number of probes - 3 subjects in each group had less than 20 probes). As shown in Figure 15, although both groups start at approximately the same meditation depth, the group of expert practitioners showed a highly significant increase from 0.034 to 0.058 points in the depth of their meditation over time, p=0.0000002; r^2 =0.8 (the ranges provided here indicate a 95% confidence interval (CI), with all statistics using parametric methods), as well as a significant increase for non-expert practitioners, p=0.02; r^2=0.27 (increase from 0.003 to 0.026 points in meditation depth per probe). No significant differences were observed in the intercept between the two groups, with a 95% confidence interval for a non-overlapping slope indicating a significant difference between the two groups. A regression analysis revealed a significant reduction over time for the mind wandering scale for the expert practitioners (p=0.02; r^2=0.27 for experts, and p=ns; r^2=0.02 for non-experts). The decrease in mind wandering for experts was significantly negative, with a slope CI of -0.033 to -0.003.

Table 1. This table presents the average response for non-expert (NE) and expert (E) meditation practitioners for the 3-question experiential probe series pertaining to the depth of meditation (Q1: Med) mind wandering (Q2: MW) and drowsiness (Q3: Sleep) as measured throughout the experimental paradigm.

	Med	MW	Sleep
Non-expert meditators			
NE1	2.64	1.27	1.09
NE2	0.82	1.55	0.08
NE3	1.6	1.56	0.48
NE4	1.14	2	0.95
NE5	2.05	0.46	0.31
NE6	0.6	1.58	1.34
NE7	1.16	1.88	0.06
NE8	1.34	1.66	0.03
NE9	1.6	2.56	1.88
NE10	0.76	1.12	0.53
NE11	1.74	1.62	0.06
NE12	1.27	1.85	1.95
Mean	1.39	1.59	0.73
Expert meditators			
E1	1.31	1.33	0.7
E2	1.2	1.09	0.7
E3	1.61	1.21	0.68
E4	1.16	0.47	0.06
E5	1.45	0.86	0.57
E6	1.43	1.17	0.07
E7	2.42	0.88	0.3
E8	2.5	1.46	1.62
E9	2.53	0.52	0.08
E10	1.95	1.4	0.28
E11	2.54	1.17	1
E12	2.07	2.14	2.21
Mean	1.85	1.14	0.69

The intercept between the two groups did not differ significantly. Interestingly, our sleep scale measures indicate that the non-expert group experienced increased drowsiness compared to the expert group at the onset of the experiment (CI of 0.62 to 0.86 at the first probe for the expert group and 0.37 to 0.61 for non-expert group) suggesting that meditation experience may potentially affect overall subjective alertness level. Additionally, the expert group reported a significantly reduced depth of drowsiness as the experiment progressed, while the non-expert group reported significantly increasing drowsiness (slope CI of -0.034 to -0.012 for experts and 0.008 to 0.029 for non-experts). Both regressions were highly significant (experts p=0.0004; r2=0.51 vs. non-experts p=0.002; r2=0.43).

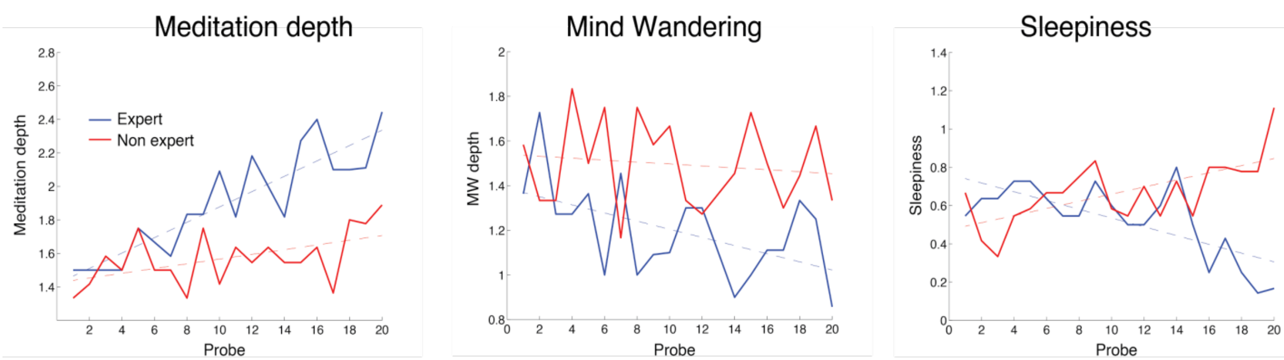


Figure 15. Evolution of the responses to experiential probes throughout the experiment for the three questions pertaining to meditation depth, mind wandering, and sleepiness. Only the first 20 probes for each subject are shown. Thick lines indicate mean response on each probe for the two groups of participants. Dashed lines indicate linear regressions. Significant results are reported in the text.

While significant behavioral differences were observed between experts and non-experts when considering mind wandering, we observed large inter-subject variations. The relatively large variance across participants was most likely due the subjective nature of the task. Participants were likely to have rated the questions differently – with some participants being biased towards providing high ratings, as compared to others being biased towards providing low ratings. This is consistent with the fact that we observed larger differences between expert and non-expert practitioners when we considered the normalized individual ratings for both the meditation and mind wandering responses, than when we considered absolute ratings. Calculating the differences between the ratings of these two questions effectively minimized the absolute response bias participants may have had. Since a comparison of ratings across participants is subject to a large amount of noise, we adopted the strategy of splitting trials in two categories: trials for which ratings on the meditation scale were larger (considered meditation trials) than mind wandering, and vice versa (mind wandering trials). Trials in which the two depth ratings for the two conditions (meditation and mind wandering) were equal were ignored. Two subjects were excluded from this analysis because they reported no behavioral trials for one of the two conditions.

Our behavioral analyses found that expert practitioners reported significantly more meditation trials as compared to mind wandering trials (mean of 75.4 trials for MED; mean of 24.6 trials for mind wandering; Standard Error (SE) of 4.4 in both cases, $p=0.00014$), while non-expert practitioners showed no such effect (mean of 42.7 trials for MED; mean of 57.3 trials for mind wandering; SE of 6.2, ns) as shown in Figure 16. Group level statistics showed that non-expert practitioners reported a significantly greater number of mind wandering trials as compared to expert practitioners (difference of 32.7; $p=0.00038$), and that expert practitioners reported a significantly greater number of meditation trials as compared to non-expert meditators (difference of 32.7; $p=0.00052$).

5.2.4.2 EEG Activity time-locked to Experience-Sampling Probes

Event-related spectral perturbation (ERSP) of the EEG signal was assessed during the 10 seconds immediately preceding probe onset (see Methods). Expert practitioners showed significantly increased modulation of theta activity (4-7 Hz) across the frontal cortex ($p<.02$ after correction for multiple comparisons), as well as alpha activity (9-11 Hz) primarily concentrated over the somatosensory cortex ($p<.02$), during meditation trials as compared to mind wandering trials. When the same analysis was conducted on the non-expert meditation group, no significant differences were observed (see Discussion). No interaction was observed between trial type and meditation expertise.

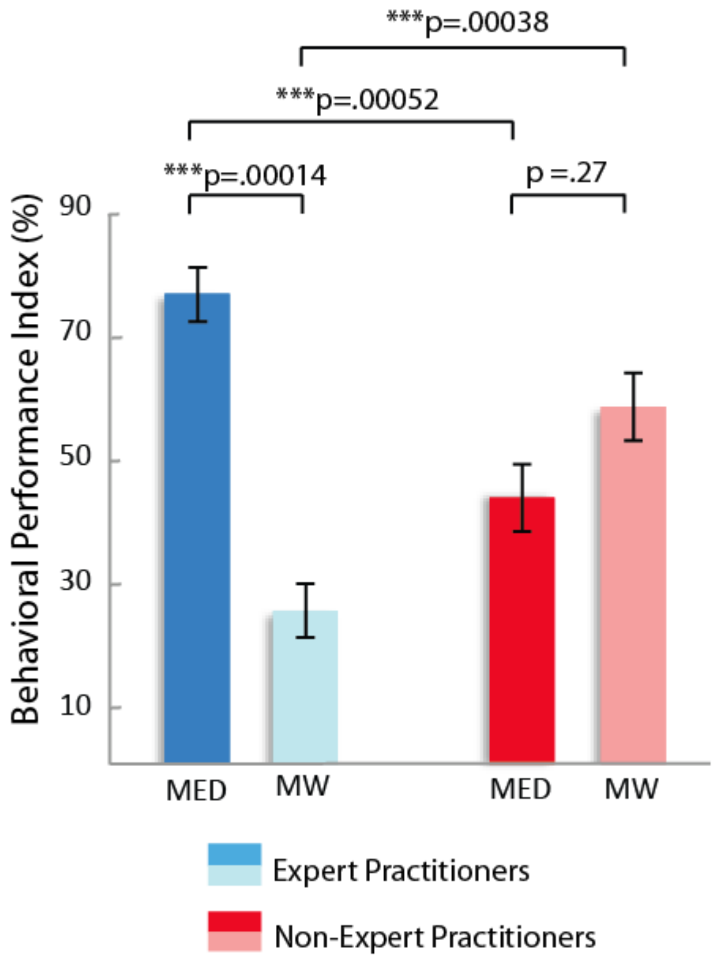


Figure 16. Expert practitioners reported a greater number of probed trials in which they were actively engaged in their meditation as compared to mind wandering. They also reported a greater number of probed trials in which they were actively engaged in their meditation than non-expert practitioners. Error bars indicate 95% confidence intervals, which were calculated by multiplying the standard error by 1.96.

For each expert subject, we averaged the theta and alpha power for the electrodes that showed significant differences in both frequency bands (Figure 17). We observed a positive correlation between theta difference between meditation and mind wandering state and alpha power difference between meditation and mind wandering state (r^2=0.42; p=0.02) indicating that subjects that had a larger theta difference between conditions also had a larger alpha difference. We did not observe correlations between behavioral responses (responses averages for expert subjects from Q1 to Q3 in Table 1) and theta or alpha power differences.

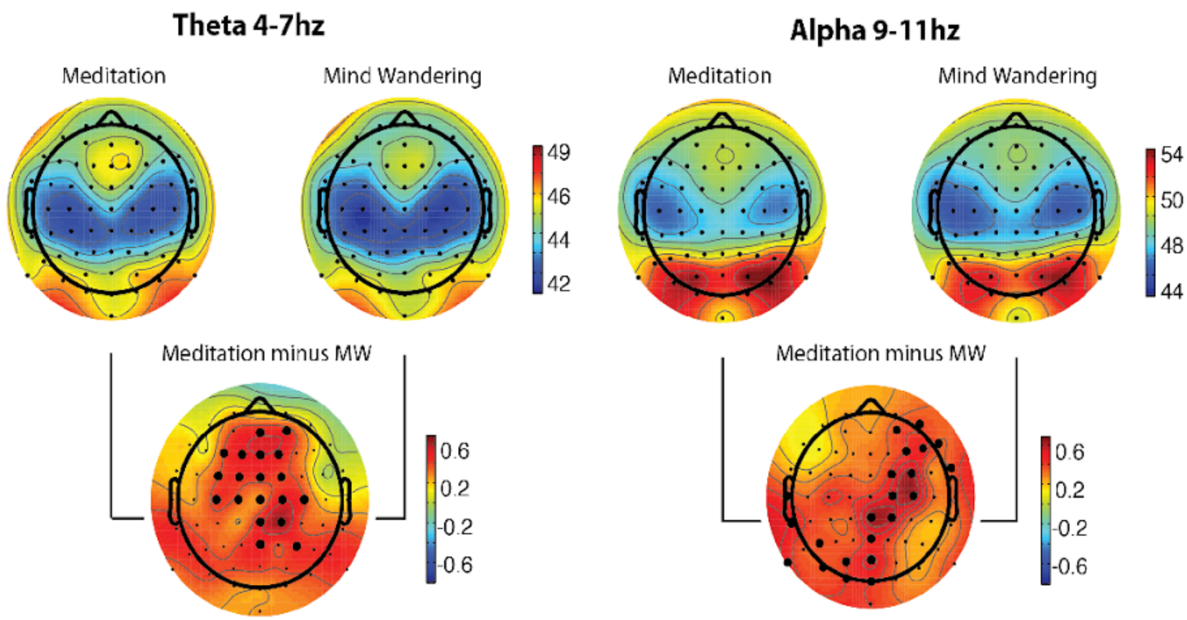


Figure 17. Event related Spectral Perturbation (ERSP) plots, and differential plots of significance in theta (4-7Hz) and alpha (9-11Hz) band activity for expert meditation practitioners. Power scales are expressed in $\mu V^2/Hz$. Black dots on the difference plots indicate electrodes significant at $p<0.02$ after cluster correction for multiple comparisons.

5.3 Discussion

Our results provide some of the first evidence that meditation expertise is associated with an attenuated frequency of mind wandering. We observed that meditation expertise was associated with a significantly greater depth of meditative absorption, and a significantly reduced number of mind wandering episodes throughout our experience-sampling paradigm. These findings suggest that meditation training reduces the susceptibility of the mind to wander, subsequently leading to longer periods of meditative absorption (discussed below). Our findings provide supporting evidence that increased theta activity over mid frontal theta regions and alpha activity primarily focused over the somatosensory cortex are markers of sustained and internally directed attentional states of awareness cultivated via long term meditation practice. Additionally, the modulations seen in mid frontal theta and somatosensory alpha, both traditionally markers of various types of executive functions, add to an expanding body of literature suggesting that meditation training may modulate some of the neural mechanisms involved in cognitive control and attention (Hölzel, Lazar, et al., 2011; Mrazek et al., 2013; Slagter, Davidson, & Lutz, 2011). Given that our limited sample size (n=24) was made of individuals who practiced exclusively in the Himalayan meditation tradition, further studies are necessary to validate our results in other meditation traditions.

Our EEG findings indicate that the mid frontal theta and somatosensory alpha rhythms, often observed during executive functioning tasks and cognitive control (Bollimunta, Mo, Schroeder, & Ding, 2011; Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015; Enriquez-Geppert, Huster, Figge, & Herrmann, 2014), can also be seen during internally guided states of focus such as meditation, and are consistent with previous research (Aftanas & Golocheikine, 2001; Kerr et al., 2013). It may also suggest a functional relationship between the sources contributing to our observed mid-frontal theta activity and the broader frontoparietal control network involved in maintaining top-down representations of goal states, learning and directed attention (Cavanagh & Frank, 2014; deBettencourt, Cohen, Lee, Norman, & Turk-Browne, 2015; Spreng, 2012). The role of theta in meditation practice and the cultivation of top-down control via the enhancement of monitoring and possibly enhanced conflict detection falls in line with the established literature regarding its specific role in learning (Haegens, Osipova, Oostenveld, & Jensen, 2010; Swick & Turken, 2002). Cavanagh & Frank (2014) have suggested that cortical theta-band oscillations may serve as a candidate mechanism by which neurons communicate top-down control over long range and broad networks. Mid-frontal theta has been proposed to function as a temporal template for organizing mid-frontal neuronal processes and theta-band phase dynamics may entrain disparate neural systems when cognitive control is needed (Cavanagh & Frank, 2014). This is supported by findings suggesting that cortical and subcortical areas are interconnected via the cingulate cortex (Morecraft & Tanji, 2009, Bollimunta et al., 2009). Our study thus provides new evidence to support the claims posited by Spreng et al. (2012) that the maintenance of both internal and external orientations of focus may be maintained by similar neural mechanisms, and our findings suggest that meditation training may target the neural substrates underlying these oscillations.

The observed increase of alpha activity in our expert meditation group supports its putative role in the processing and integration of somatosensory information (Kerr et al., 2013; Whitmarsh et al., 2014), as its role of mediation in cognitive entrainment. Somatosensory alpha modulation has been established in the facilitation of working memory performance, with mindfulness meditation practitioners showing an enhanced ability to modulate alpha power in sensory neocortex in response to a cue (Kerr et al., 2013). Kerr and colleagues (2013) suggests that mindfulness meditation enhances top-down modulation of alpha by facilitating precise alterations in timing and efficacy of the somatosensory cortex thalamocortical inputs. Thus our findings of enhanced alpha activity support these respective findings and are consistent with the hypothesis that meditation training may modulate cortical mechanisms underlying somatosensory perception. Furthermore, our findings provide further support for theories that an enhanced integration of sensory information and attention can be learned and modulated via top-down processes.

Our implementation of a probe-caught mind wandering paradigm was based on previous findings which suggest that this method is thought to reflect the actual frequency of mind wandering episodes, whereas mind wandering that is self-reported may reflect an individual's metacognitive awareness of mind wandering (Smallwood & Schooler, 2006). While meditation practice may increase the number of self caught mind wandering episodes over time by enhancing metacognitive awareness of internal experience, it may also be due to a reduced number of lapses of task-related attention following extensive training, limiting the opportunities for practitioners to subsequently identify and report mind wandering episodes. Thus, variations in reports from both self and probe caught mind wandering paradigms should be mutually considered in future studies. While our research findings do suggest that over time meditation practice may fundamentally reduce the frequency of spontaneous thought, this may occur alongside the ability to actively identify and disengage from mind wandering and subsequently reorient attention. It may also be the case that meditation practice facilitates the unification of various attentional mechanisms so as to moderate mind wandering. Future avenues of research on mind wandering and meditation training should focus on disentangling whether meditation increases the metacognitive awareness of mind wandering and the subsequent reorientation of attention, if meditation enhances a fundamental capacity of allocating attentional resources, or if meditation facilitates an overall reduction in the occurrence of mind wandering events as our findings suggest.

It remains possible that what distinguishes experts from novices is not necessarily their attentional capacity for internal focus per se, but rather their meta-cognitive capacity to accurately label mental states (Baird, Mrazek, et al., 2014). It is also important to note that due to the nature of our experimental paradigm in which participants were being auditorily probed about every 3 minutes, exit interviews indicated that the majority of participants were unable to experience particularly 'deep' meditative states. As indicated in our behavioral data, both groups experienced a progressive increase in the depth of their meditation over time suggesting that both groups progressed in their ability to engage in their meditation practice and perform the task simultaneously. Given that meditative experience enhances individuals' ability to monitor internal states, it would follow that expert meditators would also be better at labeling these states. Thus we cannot rule out the possibility that our novice meditators were engaged in focused meditative practices in a way that would be similar to experts, and that the differences in EEG we observed was due to a decreased capacity of novices to accurately label mental states. Our corresponding EEG and behavioral findings in expert practitioners may therefore provide supporting evidence for an enhanced metacognitive accuracy in reporting as a result of long term meditation practice.

Cognitive control is one of the most essential sets of cognitive functions for our interactions with the external world, with individual differences in these cognitive functions predicting success across academic and professional domains (Hirsh & Inzlicht, 2010). Research is beginning to confirm that impaired cognitive control is the hallmark of clinical disorders such as ADHD, obsessive compulsive disorder, and schizophrenia (Kaser et al., 2013; Mazaheri et al., 2014; Yordanova, Kolev, & Rothenberger, 2013). Our findings suggest that contemplative practices and techniques may be useful in treating an increasingly wide array of medical and clinical disorders through training and exercising the neural circuitry underlying the top-down regulation of executive functions, somatosensory processing and metacognition. Furthermore, they provide support for the development of cognitive protocols and brain computer interfaces that aim to modulate these neural networks and their underlying cortical and subcortical structures.

Our behavioral results are one of the first to show that an attenuated frequency of mind wandering can be considered a direct marker of meditation expertise. Furthermore, the corresponding behavioral and EEG findings in our expert practitioner group provide evidence for enhanced metacognitive accuracy in reporting as a result of long term meditation practice. Finally, the increased mid frontal theta and alpha rhythms observed during meditative absorption provide direct evidence to support the hypothesis that the maintenance of both internal and external orientations of focus may be maintained by similar neural mechanisms.

Chapter 6: Frontal Midline Theta and Cognitive Control

6.1 The Prefrontal Cortex and Theta Oscillations

The increasing interest in neuronal oscillations has resulted from findings revealing the complex dynamics of individual neurons, including their intrinsic abilities to resonate and oscillate at multiple frequencies (Buzsáki, 2004; Hutcheon & Yarom, 2000). This suggests that the processing of information may be integrated across multiple temporal and spatial scales, and that a hierarchy of mutually-interacting oscillations may systematically interact in a manner that regulates integration (Canolty & Knight, 2010; Fries, 2005; Lakatos et al., 2005; Palva, Linkenkaer-Hansen, Näätänen, & Palva, 2005). These findings would suggest that the exact timing of neuronal activity across networks could represent information. Supporting evidence for this comes from research demonstrating that structures of neural assemblies show oscillatory patterns during sleep that are directly linked to the experiences of individuals in the awake period immediately preceding the sleep (Buzsáki, 1998; Buzsáki & Draguhn, 2004). Taken together, these findings suggest that perception, memory, and possibly even consciousness may come from the synchronization of neural networks (Buzsáki, 2007).

A large body of accumulating research has established the significant relationship between synchronous neuronal oscillations and cognitive functions. Neural oscillations are sinusoidal rhythmic fluctuations in electrical activity throughout the brain, with specific frequency bands generated by the integration of specific and distinct biophysical and cellular properties (Canolty & Knight, 2010; Quilichini, Sirota, & Buzsáki, 2010), and are thought to reflect rhythmic changes in cortical excitability (Fries, 2005; Schoffelen, Oostenveld, & Fries, 2005). These oscillations can be influenced by large-scale patterns of connectivity, and have been measured throughout the nervous system, spanning impressive spatial distances and temporal scales in the mammalian brain (0.5-500 Hz; Buzsáki & Draguhn, 2004). Given that synchronous oscillations occur within local populations of neurons, as well as across large neuronal populations within broader neural networks, one theory underlying neural communication and learning implicates slow, long range low frequency mechanisms (György Buzsáki & Draguhn, 2004; Varela, Lachaux, Rodriguez, & Martinerie, 2001). It has been suggested that the given size of a functional brain network may determine its oscillatory frequency, therefore the larger and more distributed the network, the slower the underlying oscillation (von Stein & Sarnthein, 2000). It has been suggested that oscillations regulate network communication through coherence (Bastos, Vezoli, & Fries, 2015; Canolty et al., 2006) and contribute to memory formation (Rutishauser, Ross, Mamelak, & Schuman, 2010) and cognitive control (Mishra & Gazzaley, 2015).

Modern theories on the role of brain oscillations in computation generally suggest that oscillations form a cyclic temporal reference frame for organizing information processing (Cohen, 2014). Electrophysiology research on memory (Kahana, Seelig, & Madsen, 2001), feedback and feedback-driven learning (Marco-Pallares et al., 2008; van de Vijver, Ridderinkhof, & Cohen, 2011) and other cognitive control processes (Cavanagh, Figueroa, Cohen, & Frank, 2012) provide accumulatively convincing evidence that theta band oscillatory activity may serve as the underlying "language" of the prefrontal cortex for local and network wide communication (Cavanagh & Frank, 2014; Cohen, 2014). This may be because the intrinsic architecture and structure of the prefrontal cortex supports the generation and maintenance (rhythmogenesis) of theta-band activity, and that specific and local neural computations are what account for fluctuations in EEG (Cohen, 2014). In this light, the functional implication is that MFC theta may provide a reference frame for monitoring and adjusting temporally sequenced actions, functioning as a hub for theta phase-synchronized information transfer (Cavanagh & Frank, 2014; Cohen, 2011; Cohen, 2014).

Cognitive control refers to our capacity to optimize goal-directed behavior when faced with competing response alternatives (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Richard Ridderinkhof, Forstmann, Wylie, Burle, & van den Wildenberg, 2011). Research has linked many of the cognitive processes involved in learning, short term memory, and adaptive control mechanisms to neural networks in the frontal cortex (Fuster, 2000a, 2000b; Miller, 2000), with the medial frontal cortex (MFC) signaling the need for increased control during challenging or conflicting circumstances (Alexander & Brown, 2014). The MFC, in addition to the dorsolateral medial PFC is thought to have top-down influence over bottom up task-related sensorimotor processing (Cohen, van Gaal, Ridderinkhof, & Lamme, 2009; Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011; Egner & Hirsch, 2005) and facilitate changes in future behavior (Kerns et al., 2004). Recent anatomical studies have shown that an overlapping region of the dorsal cingulate — the anterior midcingulate cortex (aMCC) has been implicated in negative affect, pain and cognitive control, suggesting a functional relationship that reflects control processes common to all three domains (Shackman et al., 2011). The aMCC is a highly interconnected brain structure that functions as a main hub in the broader cognitive control network (Niendam et al., 2012)

Frontal midline theta (FMθ) is a topographically localized theta oscillatory activity recorded over medial-frontal electrodes (Fz, Fcz), and has been associated with higher cognitive functions such as executive functioning, conflict detection and optimal adjustments of behavior facilitating adaptive control (Shackman, et al., 2011; Shenhav et al., 2013; Cavanagh & Shackman, 2015). While EEG generally entails a lack of spatial specificity, evidence from EEG source estimation (informed by MRI), along with invasive recordings in humans and monkeys (Tsujimoto, Shimazu, Isomura, & Sasaki, 2010; Wang, Ulbert, Schomer, Marinkovic, & Halgren, 2005) suggests that FMθ activities are generated by mid-cingulate cortex (MCC) and pre-Supplemental Motor Area (Cavanagh & Frank, 2014; Mitchell, McNaughton, Flanagan, & Kirk, 2008). Other findings suggest that the FMθ implicated in cognitive control is encoded by rhythmic activity generated by the anterior cingulate cortex (ACC; Womelsdorf, Johnston, Vinck, & Everling, 2010). It is important to note that large intra-individual differences, including the presence of additional sulci in approximately half the population, have been observed in the macroscopic anatomy of the cingulate and present an obstacle in resolving the subtle details in the regions functional organization (Shackman, et al., 2011). However, it remains clear that FMθ is generated during the need for cognitive control, with accumulating research suggesting that it may function as a mechanism for implementing top-down control across broad networks (Canolty et al., 2006; Cavanagh & Frank, 2014; Fries, 2005; Shackman et al., 2011). FMθ activity has been predominantly observed as event-related potential (ERP) components elicited by novel information such as conflicting stimulus-response requirements that evoke a need for increased cognitive control (Cohen, 2014; Cavanagh & Frank, 2014). Increases of FMθ have also been shown to predict successful behavioral performance and have been related to efficient WM maintenance (Jensen et al., 2007; Tóth et al., 2014). It is important to distinguish that the spatial–temporal characteristics of theta oscillations that have been observed during retrieval and memory encoding are generally temporally sustained and found across various prefrontal areas, and may therefore differ from the mid frontal theta observed during response conflict (Cohen, 2014). FMθ coherence (as compared to peak and mean amplitude) may function as a binding mechanism facilitating functional connectivity (Mitchell et al., 2008) in the form of information exchange, the modulation of synaptic plasticity (Fries, 2005), the signaling of the need for control via the entrainment of other brain networks, and indicate how the need for control is biophysically realized and communicated (Cavanagh & Frank 2014).

6.2 FMθ, Learning and Neural Plasticity

Research suggests that the MCC is strongly interconnected to cortical and subcortical areas and plays a critical role of information integration during goal directed behaviors (Lezak, 2012), executive functioning, and may facilitate the mechanisms for general action monitoring, through the entrainment of spatially distal functional networks via FMθ signals during cognitive control (Cavanagh et al., 2012; Cavanagh & Frank 2014). Learning in the neocortex can be expressed by prediction errors that signal the need for network-wide adaptation, and are thought to enhance the future predictability and conserve cognitive resources (Dehaene et al., 1998; Friston, 2010). Increasing evidence would suggest that transient increases in FMθ reflect general surprise and detection of both endogenous and exogenous events (Friston, 2005), and may function to influence behavior through the enhanced sensory processing and the reallocation of attention (Mitchell et al., 2008). Thus, FMθ may function as a temporal template carrying higher information content signals such as gamma band activities via cross-frequency coupling (Figure 18; Canolty et al., 2006; Fries, 2005). Cavanagh & Frank (2014) suggest that the synchronous phase relationships that have been observed in frontal areas may not reflect the transfer of specific information related stimuli which evoke conflict processing, but rather a broader mechanism which organizes neural processes during decision points where executive functioning is needed, facilitating neural adaptation and lower level learning (Aston-Jones & Cohen, 2005; Cavanagh & Frank, 2014; Singer, 2013).

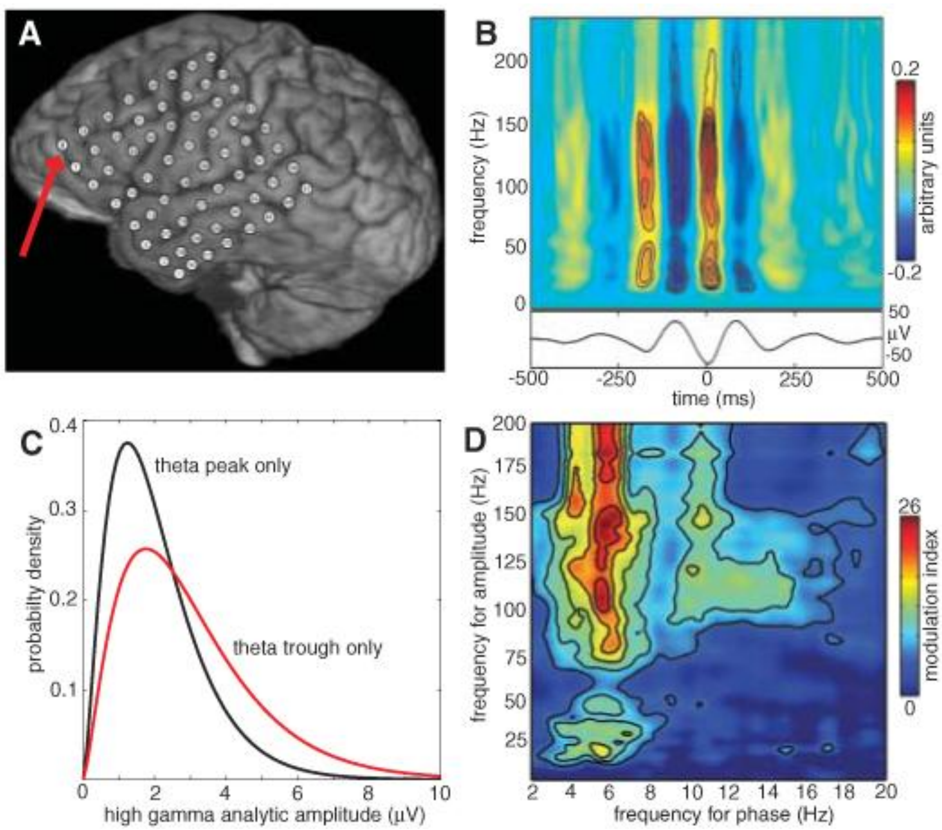


Figure 18. This figure shows that high gamma (80 to 150 Hz) power is modulated by theta (4 to 8Hz) phase. Plot A shows the MRI locations of the 64-channel ECoG grid (resting over frontal and temporal lobes). Plot B shows phase-locked modulation of power over the anterior portion of the middle frontal gyrus. Plot C shows the best-fit gamma distributions that occurred at the peak (black) trough (red) in radians of the theta waveform shown in plot B. Plot D is a modulation index as a function of analytic amplitude (5 to 200 Hz) and analytic phase (2 to 20 Hz) for the same electrode. (Canolty et al., 2006)

Given that long range neural inputs are likely to facilitate control over local inhibition and induce synchronous phase relationships (Buzsáki, 2004, 2010), a large variety of cognitive functions may be facilitated through the wide spread connections between the MFC and other brain areas (Fries, 2005; Phillips, Vinck, Everling, & Womelsdorf, 2014). Benchenane and colleagues (2010) proposed that FMθ coherence may be due to an increase of dopamine modulated interneuron inhibition of pyramidal cells, after observing increased coherence in hippocampal-FMθ following the administration of dopamine in the prefrontal cortex of anesthetized rats. Similar to the findings of Buzsáki (2004) in humans, Benchenane and colleagues found the activity in cell assemblies in the prefrontal cortex that emerged during increased FMθ coherence were replayed preferentially during subsequent sleep. Their interpretation was that coherence between the prefrontal cortex and hippocampus may lead to the synchronization of reward predicting activity in prefrontal networks, which are then tagged for later memory consolidation. Interestingly, research has shown that the MFC neurons differ from other cortical regions in terms of density, biophysical and anatomical properties. Their specified theta band bursting properties combined with strong reciprocal excitatory (AMPA mediated) interconnections are thought to facilitate dopamine modulated short-term plasticity (Cohen, 2014; Holroyd & Coles, 2002; Jocham & Ullsperger, 2009). The neural mechanisms underlying such plastic changes in white matter involve the repeated activation of the specific neural pathways during learning in rats, primates and humans (Gibson et al., 2014; Wang & Young, 2014), and have also been evidenced by mental training methods such meditation (Tang & Posner, 2014).

6.3 A Neural Marker for Training Cognitive Control

As evidenced in our previous study (Brandmeyer & Delorme, 2016) advanced meditation practitioners exhibited increased FMθ activity during reported periods of sustained concentration meditation, suggesting an increased capacity for sustained attention and enhanced top down control. Additional recent research found similar increases in FMθ and temporo-parietal theta power in meditators during meditative absorption (DeLosAngeles et al., 2016). Based on our previous research findings in advanced meditation practitioners who elicit this activity while engaged in a concentrative meditation technique (Brandmeyer & Delorme, 2016), alongside the enhanced cognitive processing and improved task performance associated with increased FMθ power (e.g., Klimesch, Doppelmayr, Russegger, & Pachinger, 1996; Mitchell et al., 2008), cortical FMθ oscillations may be an ideal candidate for protocols aimed at training and improving cognitive control, with possible transference to cognitive faculties that fall under the broader executive functions umbrella (Enriquez-Geppert, Huster, Figge, et al., 2014). Empirical research findings suggest that neural mechanisms underlying sustained attention heavily rely on FMθ phase synchronization, along with selective excitation and inhibition of cognitive processing through alpha and gamma oscillations, and their respective interactions across attention-related neural networks (Fries, 2005; Cavanagh & Frank 2014).

Cortical oscillations can be trained and amplified by voluntary control as evidenced by training such as meditation (Brandmeyer & Delorme, 2016). However, a study by deCharms and colleagues (2005) suggests that sensory feedback is crucial for training self-regulation. They found that successful modulation of the neural activity associated with pain perception was only successful when subjects were presented with sensory feedback (visual, auditory, tactile). Given that chronic pain patients already experience an abundance of sensory information regarding their personal pain levels, alongside the strong will to reduce the pain, these findings provide further evidence for the immense potential feedback protocols may present. Several neurofeedback studies have already attempted to target the theta, alpha, beta or sensorimotor rhythms in an attempt to train attention (Egner & Gruzelier, 2004; Kaiser et al, 2000; Arns et al., 2009), memory (Nan et al., 2012; Staufenbiel, Brouwer, Keizer, & van Wouwe, 2014; Wang & Hsieh, 2013) and executive functions (Hanslmayr, Sauseng, Doppelmayr, Schabus, & Klimesch, 2005; Zoefel et al., 2011). However the identification of which specific frequencies are associated with a given cognitive function has been a historically debated topic (Enriquez-Geppert, Huster, Scharfenort, et al., 2013; Ghose & Maunsell, 1999). In order to establish effective and reliable neurocognitive protocols that may be able to improve cognitive control or aid in facilitating certain types of mental activity, further research is needed. Based on our previous research findings in advanced meditation practitioners who elicit this activity while engaged in a concentrative meditation technique, and that enhanced high-order cognitive processes and improved task performance has been associated with an increase of FMθ (e.g., Mitchell et al., 2008, Klimesch et al., 1996), cortical theta-band oscillations may be a plausible mechanism by which neurons could communicate top down control across broad networks, and serve as an ideal parameter for protocols aimed at improving cognitive control mechanisms.

Chapter 7: Investigating FMθ Neurofeedback

7.1 FMθ and Neurofeedback

Recent advancements in the technological sector have merged with the neuroscientific insights into the nature of cortical oscillations revealing a unique capacity of humans to voluntarily control and interact with our own neural activity when presented with real time sensory feedback. Traditionally, neurofeedback has been based on session-to-session or trial-to-trial modulations of continuous neural activity, and can be used to modulate and modify cortical oscillations (Enriquez-Geppert, Huster, Scharfenort, et al., 2013; Enriquez-Geppert, Huster, & Herrmann, 2013). During neurofeedback, participants actively engage in real-time online feedback of their own brain activity in order to learn how to influence their brain functions. This closed feedback loop capitalizes on the widely understood principles of operant conditioning.

The early neurofeedback studies in the 1960's on primates provided evidence for the operant conditioning of single cell spike trains in the motor cortex, as well as provided preliminary evidence for volitionally controlled and modulated neural activity through feedback based on ERPs and spectral power (Fetz 1969; Kamiya, 1968; Kamiya, 1969). Several more recent and sophisticated EEG and electrocorticogram (ECoG) based brain-computer-interface (BCI) studies have now gone so far as demonstrate that by modulating neural activity in motor-related areas of the cortex they were able to restore motor function in patients with Tetraplegia (Wang et al., 2013). While neurofeedback was pushed to the sidelines back in the 1980s after a series of misleading publications that contained methodologically flawed and overly simplified protocols (Gruzelier, 2014), more recent protocols implementing neurofeedback via oscillatory rhythms, cellular activity (Cerf et al., 2010; Ishikawa et al., 2014; Clancy et al., 2014), near infrared spectrometry (NIRS; Kober et al., 2014; Mihara et al., 2012), the hemodynamic response (deBettencourt et al., 2015; deCharms, 2008; Hamilton, Glover, Hsu, Johnson, & Gotlib, 2011; Rota et al., 2009; Zotev et al., 2011; Birbaumer et al., 2013), transcranial doppler sonography (Duschek, Schuepbach, Doll, Werner, & Reyes del Paso, 2011), and transcranial magnetic ultrasound (Hameroff et al., 2013) have all contributed to its resurgence within the scientific community, as well as to the expanding prominence and popularity of various forms of 'brain training' that have become highly fashionable in contemporary culture (Owen et al., 2010; Rabipour & Raz, 2012). In clinical settings, neurofeedback has been effectively used in the treatment of attention deficit hyperactivity disorder (ADHD) with lasting results (Birbaumer et al., 2009; Gani et al., 2008). Research findings suggest that neurofeedback training has led to improved cognition as well as the neurophysiological functioning in healthy subjects (Egner and Gruzelier, 2001). Given the increasing interest and popularization, the inexpensive and non-invasive nature, and the immense potential for the applications of neural self-regulation in the restoration and improvement of cognitive functions in both public and clinical contexts, further scientific study and validation of specific scientific protocols is crucial.

Cognitive control is thought to enable the planning, controlling and monitoring of complex, goal-directed behavior and thoughts (Baumeister, 2002) and is associated with various behavioral and neurocognitive impairments when disrupted (Goldberg & Seidman, 1991). As discussed at length throughout this thesis, cortical oscillations have been clearly demonstrated to serve as an index of both sensory and cognitive processes such as cognitive control (Başar, Schürmann, & Sakowitz, 2001; M. X. Cohen & Cavanagh, 2011; Mishra & Gazzaley, 2014), the regulation of network communication, the mediation of long-range integration (Bastos et al., 2015; Canolty & Knight, 2010), memory formation (Rutishauser et al., 2010), and represent one of the most promising candidates for the implementation of training voluntary top-down control mechanisms. However for both clinical and public applications it is of great importance that research clearly identifies and implements protocols based on established relationships between specific oscillations and their corresponding cognitive processes. Based on our previous findings (Brandmeyer & Delorme, 2016) demonstrating that advanced meditation practitioners show enhanced FMθ activity during focused meditation, and in light of the multitude of neurofeedback systems claiming to train meditation using gross measurements and forms of feedback, we designed a neurofeedback protocol that to our knowledge, is the first to train a neural correlate, as well as meditation inspired techniques, derived from advanced meditation practitioners. In a study by Colier et al. (2016), intracranial FMθ training was found to modulate firing rates and spike timing, as well as induce increased FMθ and gamma cross-frequency-coupling, demonstrating that changes in temporal and local level network dynamics could be implemented by the control of oscillations in a neurofeedback paradigm, subsequently selectively potentiating and reorganizing pre-existing circuits. While these studies are invaluable to our understanding due to their fine grained methodologies and data, scalp EEG studies are necessary for the development of non-invasive use of neurofeedback in the general population.

Research investigating the efficacy of NFB has demonstrated that approximately 25% of participants that undergo neurofeedback protocols can be considered non-responsive (Zoefel et al., 2011). This may be due to a wide number of reasons including ineffective strategies or lack of motivation. In terms of the percentage of positive neurofeedback reward that should be given, various reports indicate that this remains under debate. While 80% positive feedback has been considered to be too high for optimal learning (Arns et al., 2014), too low of a percentage prevents the subjective experience of feeling in control. It has been suggested that a moderate amount (50%) of positive feedback may increase the generation of the desired behavior during NFB and thus transfer more easily into daily life. Furthermore, increased temporal lags within training and between training sessions may enhance training gains (Ebbinghaus, 1964). Neurofeedback training gaps are based on two time scales: gaps between days, and the gaps within a given neurofeedback session. In general, two types of neuronal consolidation can be distinguished: synaptic vs. system consolidation. After the first hours of training synaptic plasticity takes place, including the formation of new connections and the restructuring of existing ones (e.g., Dudai, 2004). Since research investigating the differential effects of training lags is an important step for optimizing training protocols, the current protocol implemented mandatory 2 to 3 minute breaks between each 5 minute neurofeedback session, during which subjects made detailed notes of their mental strategies implemented in the previous session. Additionally, each Neurofeedback session was recorded at exactly the same time each day for each subject respectively in order to assure that exactly 24 hours had passed between each say of training. To our knowledge, this is the first study to implement such a rigorous timing protocol. In clinical settings neurofeedback training typically incorporates a large number of training sessions (up to 40 sessions), however protocols in healthy participants have successfully demonstrated positive results with significantly fewer training sessions (Zoefel et al., 2010).

Sleep also significantly contributes to consolidation as during sleep a so-called “replay” of memory might take place (e.g., Huber, Ghilardi, Massimini, & Tononi, 2004). Spontaneous low frequency neural oscillations, rhythmic spike bursts, and spike trains fired by thalamic and neocortical neurons that occur during heightened vigilance have previously been linked to the mechanisms underlying neuronal plasticity. These mechanisms are very similar to those that characterize slow-wave sleep, suggesting that slow-wave sleep may function to consolidate memory traces acquired during wakefulness in corticothalamic networks (Steriade, 2003). On the other hand, system consolidation refers to the slow reorganization of neural circuitry, most likely reflecting the stabilization of the newly formed memories (Frankland & Bontempi, 2005).

The current study aims to examine the efficacy of FMθ feedback implementing strategies based on meditative techniques and states. Whereas previous protocols have instructed subjects to engage in specific cognitive/mental strategies (Enriquez-Geppert, Huster, Scharfenort, et al., 2014), in the current paradigm, subjects were instructed to relax, focus on their breathing, slowly count or engage in body scanning as possible methods for discovering which strategies worked best for them. Furthermore, while previous research investigating FMθ used individualized peaks of theta (Enriquez-Geppert, Huster, Scharfenort, et al., 2014), we implemented our feedback based on a 3.5 - 6.5 Hz average for several additional reasons. Firstly, recent research has highlighted the existence of several different generators of theta in the frontal cortex, all of which potentially contribute to a variety of different forms cognitive control (Cavanagh & Frank, 2014), despite having different corresponding theta peaks and underlying neural microcircuitry (Cohen, 2014). Since it may the case that the frontal theta observed during meditation reflects a broader form of cognitive monitoring and control, it is our assumption that by choosing a specific peak frequency, subjects may not find an appropriate strategy that corresponds to an accumulative increase in FMθ power, which may reflect several different generators which independently contribute to the FMθ power measured by EEG over electrode Fz.

We were also interested in examining the relationship between FMθ neurofeedback success and brain morphology, which has been linked to the generation of FMθ (Enriquez-Geppert et al., 2013b). Additionally, we were interested in examining structural, functional, and white matter changes before and after training. Thus, we designed an eight-session protocol, preceded and followed by structural and functional MRI scans, however these results have yet to be analyzed and will therefore not be presented here. To our knowledge, this is most methodologically rigorous neurofeedback study to investigate the effects of FMθ neurofeedback training to date. We also included a sham-NF group, which received mock or sham feedback based on age and gender matched controls. Subjects provided written descriptions of their experience, strategy and motivation to assess the comparability of both subject groups with respect to motivation, commitment and perceived training difficulty. Our hypothesis was that we would observe an increase in FMθ in our neurofeedback group as compared to the sham group.

7.2 Methods I General

7.2.1 Participants

Twenty-four right-handed healthy participants (12 women; mean age =25 years; SD = 3 years) participated in the NF experiment. All subjects were informed of the protocol, schedule and goals of the experiment, provided written consent, and had normal or corrected to normal vision. The protocol was also approved by the *Comité de Protection des Personnes (CPP) de Toulouse II Sud-ouest*. Twelve participants were randomly assigned to the experimental NF group (6 women), and the other twelve to the sham group (6 women). Subjects received 10 euros per hour during the Neurofeedback, and 15 euros for each 30 min MRI session. All of the participants in the sham feedback group viewed the recorded and replayed feedback from a real neurofeedback participant who was matched for age and gender. This was done in order to normalize study and visual statistics, as well as to explore whether the sheer witnessing of the feedback mediated EEG activity and or behavioral measures.

7.2.2 Experimental Protocol

Participants received either a neurofeedback or sham-NF training over the course of eight training sessions within two consecutive weeks. All participants met with the medical examiner prior to the beginning of the experiment in order to ensure MRI safety. The MRI recording session took place on the first Monday and the last Friday, and lasted ~30 minutes. Neurofeedback training sessions were conducted from Tuesday to Friday in the first week, and from Monday to Thursday in the second week (see Fig. 19). The first Tuesday and last Thursday was dedicated to the collection of the Executive Functioning Battery (EF battery; ~40min) pre and post the Neurofeedback training, respectively. Each Neurofeedback training session consisted of six 5-min training blocks, separated by short 2 to 3 minute breaks. During these breaks, participants were instructed to write down the strategies they applied within the last NF block. The 5-min training blocks and reporting on strategies were implemented to encourage continuous application of strategies and to prevent concentration declines. Both MRI and EEG Neurofeedback sessions were recorded at the same time of day for each individual subject.

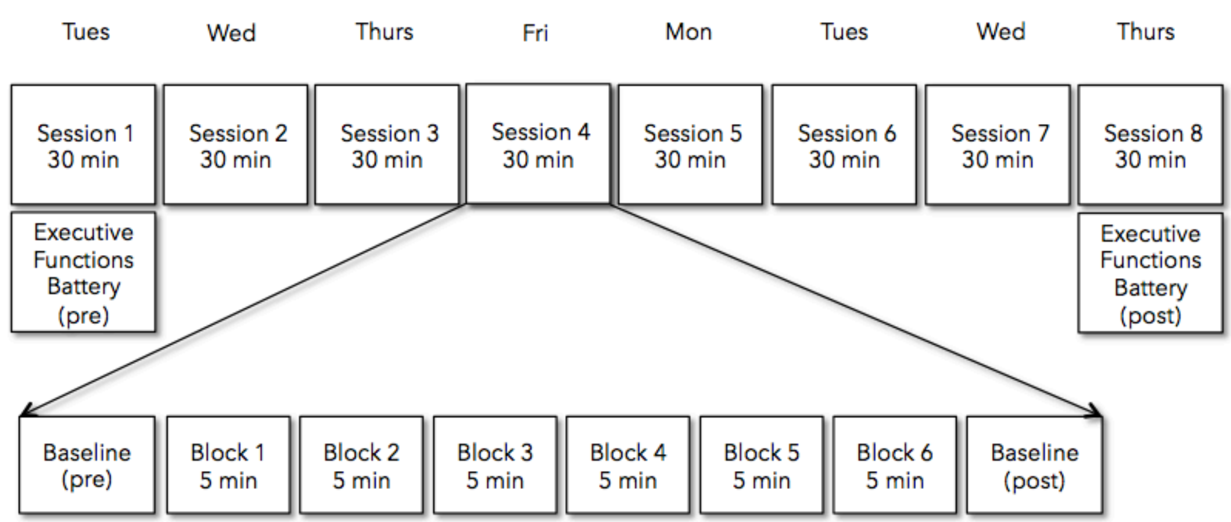


Figure 19. This figure presents an overview the two-week EEG Neurofeedback Protocol.

7.2.3 EEG Recordings

Data were collected using a 64 channels Biosemi system and a Biosemi 10-20 head cap montage at 2048 Hz sampling rate for the first and last day of the protocol. All electrodes were kept within an offset of 15 using the Biosemi ActiView data acquisition system for measuring impedance. Day 1 and Day 8 included the pre and post executive functioning assessments in addition to the first and last session of Neurofeedback. For the remaining Neurofeedback sessions (Day 2 - Day 7) EEG activity was recorded from 8 electrodes locations: Fpz, FZ, F7, F8, Cz, P7, P8, Oz. For the Neurofeedback, EEG data were processed online using Lab Streaming Layer Software (LSL) by Biosemi, and the visual stimuli were generated and presented using PsychToolbox in Matlab (The Mathworks, Inc.). During training, fast Fourier-transforms (FFT; using a hamming window) were computed every 250 ms based on 3 s data windows; hence, analysis windows showed an overlap of 2750 ms. This setup was chosen to provide the participants with a rather smooth appearance of the visual feedback by avoiding sudden jumps in the feedback colors. Artifact rejection was processed online using the method of Artifact Subspace Reconstruction (Figure 20, ASR; Mullen et al. 2013).

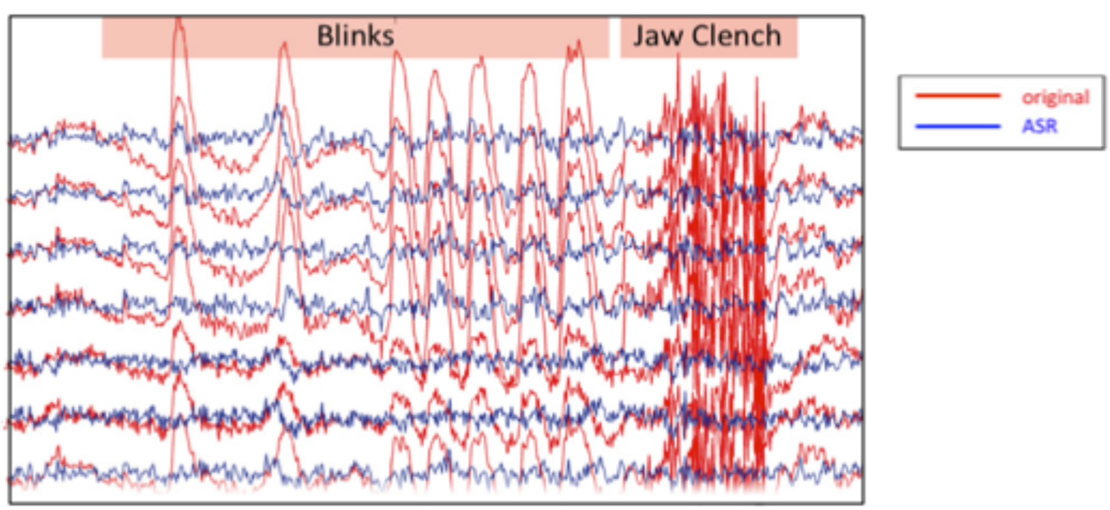


Figure 20. Artifact rejection was processed online using a sliding window PCA method of Artifact Subspace Reconstruction (ASR) based on the resting baseline as a calibration dataset 7.3 Methods II Neurofeedback

7.3.1 Neurofeedback training and its implementation

EEG was measured for 1 min (start baseline), followed by six training blocks of five minutes each (block 1–6). At the end of a training session a second resting EEG measurement was conducted (end baseline, 1 min). The ASR artifact rejection algorithm was also used during the initial baseline recording in order to optimize the filtering for later feedback sessions (default parameters of the ASR algorithm were used). Note that a bug in the program made that the state of the ASR filter was not propagated properly from one data block to the next. This did not affect the feedback session but, since the data was saved after ASR processing, this required post-processing to remove the artifacts before off line analysis – note that we also have the data before ASR processing but did not deem it necessary to use it.

During NFB sessions subjects were instructed to apply strategies such as, relaxing, focusing on their breath, and counting to increase FMθ amplitude relative to the amplitude during resting EEG. Feedback was given by means of a colored square. The color ranged from a highly saturated blue over white – 0000FF RGB code - to a highly saturated black - 000000 RGB code. Depending on the actual FMθ amplitude, the color was changed to blue whenever the amplitude was enhanced and to black when it was attenuated relative to the baseline measurement. Blue and black values corresponded to amplitudes above and below the actual start baseline, respectively. Participants were informed to use those strategies that would favor a highly saturated and prolonged blue-coloration of the square, and documented their strategies at the end of each 5 min block (Figure 21). Whilst the NF group received real-time feedback of their own brain activity, the sham-NF group received a playback of the feedback of a matched participant of the NF group recorded during the corresponding training session and block. During the start baseline of every training session, the amplitude of the FMθ was calculated as the mean over all artifact-free 1-second FFT windows as reference for the feedback during the training blocks. During the six training blocks, feedback was given based on the FMθ measured at eight previously specified electrodes relative to the FMθ amplitude of baseline FMθ. Instantaneous FMθ power was compared to the minimum and maximum FMθ power to compute the percentage of FMθ power, and the color of the square was made proportional to the percentage of FMθ power (with 0 percent as black and 100% as blue). An additional mechanism to slowly change the min and the max FMθ power values was added to allow for subjects to continuously increase the respective FMθ power across the training session. Every second, the min and max limits are reduced by 0.1% of the limit range, which facilitates the modulation of the color for the subject. However if the values for a given subject exceed these limits (very low or very high FMθ power), the boundary is increased by 1% of the limit range in order to increase the difficulty and promote learning.

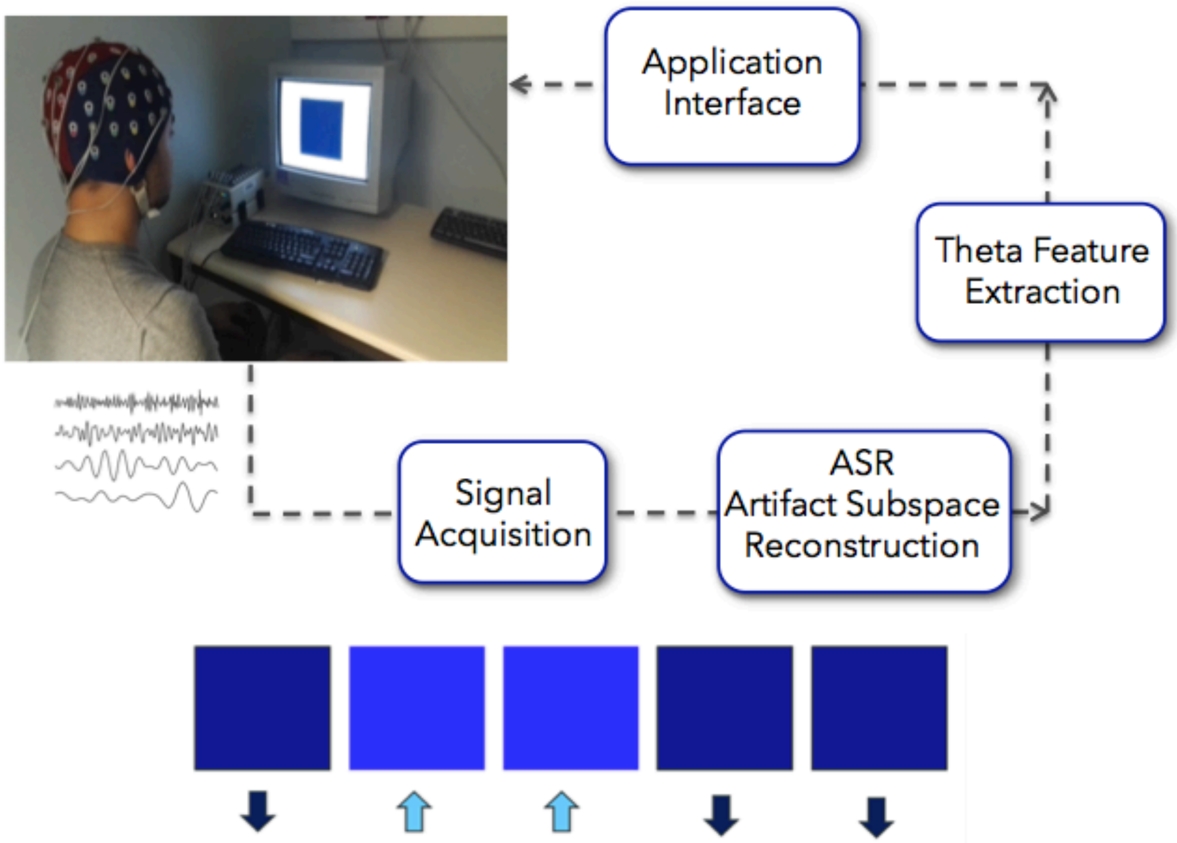


Figure 21. Neurofeedback protocol; a loop converts in real-time as the data record of a blue square whose color changes. Example of interface changes depending on the FMθ power of the subject.

7.3.2 Neurofeedback Data Processing

Neurofeedback data was EEG data was downsampled from 2048 Hz to 256 Hz and processed offline in Matlab (Mathworks, Inc.) and EEGLAB (Delorme & Makeig, 2004) in order to compute time frequency and spectral differences. While the Neurofeedback had been filtered and processed online using the ASR artifact rejection software, additionally we manually removed several bad electrodes (an average of 6 per electrodes per subject), and ran an automated rejection of bad epochs containing paroxysmal activity and bad channels to potentially address artifacts that were not removed online. For Neurofeedback we used synced desktop computers running the Matlab Psychophysics toolbox (v3.0.8) under Windows 7 operating systems. Stimuli were presented on a 17” DELL M781 mm CRT computer screen set to 75 Hz with a resolution of 800 × 600.

7.3.4 Responders vs Nonresponders

As previous studies showed that a subset of subjects does not respond to NF training (e.g., Fuchs, Birbaumer, Lutzenberger, Gruzelier, & Kaiser, 2003; Hanslmayr et al., 2005 Lubar et al., 1995) we additionally report descriptive statistics separately for responders and non-responders.

7.3.5 Statistical analyses: training effects on frequency amplitudes

For the analyses of NF success, the relative change in FMθ amplitude across all six NF blocks for each session (1–8) was quantified as change in microvolts and percent relative to the corresponding values of the first training session. To investigate the specificity of training success this calculation was not only performed for FMθ, but also for alpha and beta activity. Furthermore, resting EEG was calculated as the mean of the start and end baseline measurements per session (1–8) relative to FMθ amplitude observed during the baseline measurements of the first session. This calculation was performed for the alpha and beta resting amplitude as well. Training effects were analyzed by repeated-measures ANOVA with the factors session (1–8) and group (NFB vs. pseudo NF) for training amplitude. To investigate the course of FMθ amplitude increase during training, a regression line was fitted for each subject.

To test if gradients were different between groups (NFB vs SHAM) a one-tailed independent-samples t-test was calculated for the slope and the intercept (III). As last step, training effects on resting EEG were analyzed as well, again using repeated-measures ANOVA with factors session (1–8) and group (NFB vs. pseudo NFB) for (IV). In cases of sphericity violations, Greenhouse–Geisser corrections were performed; corrected p-values as well as ε-values are reported.

7.3.6 Statistical analyses: dynamical changes within Neurofeedback sessions

A further method to identify changes due to NFB is the analysis of changes within sessions compared to the baseline measurements (see for example Dempster & Vernon, 2009). Thus, training amplitude for each experimental block was extracted and averaged across all sessions (start baseline, block 1, block 2, block 3, block 4, block 5, block 6, end baseline) for FMθ, alpha, and beta frequencies relative to the amplitude observed during the first start baseline as change in mV and percent. Effects were analyzed by a repeated-measures ANOVA (implemented as a general linear model in the Statistica software) with factors block (start baseline,block 1, block 2, block 3, block 4, block 5, block 6, end baseline) and group, NFB vs pseudo NFB.

7.4 Methods II Executive Functioning Battery

7.4.1 N-back Task

One the first and last day, subjects performed an N-back task. For all stimulus presentations, we used a desktop computer running the Matlab Psychophysics toolbox (v3.0.8) under Windows 7 operating systems. Stimuli were presented on a 17” DELL M781 mm CRT computer screen set to 75 Hz with a resolution of 800 × 600. Subjects performed a visual sequential letter n-back task, with memory load ranging from 1- back to 3-back (Figure 20). The visual stimuli consisted of a sequence of 4 letters (A, B, C, D) presented black on a grey background. The participants observed stimuli on a visual display and responded using the spacebar on a keyboard. In the 1-back condition, the target was any letter identical to the trial immediately preceding one (i.e., one- back). In the 2-back condition, the target was any letter that had been presented two trials back, and in the 3-back condition, the target was any letter presented three trials back. In this way, working memory load varied from 1 to 3 items. Stimuli were presented on the screen for a duration of 1 second, after which a fixation cross was presented for 500 ms. Participants responded to each stimulus by pressing the spacebar with their right hand upon target presentation. If no spacebar was pressed within 1500 ms of the stimulus presentation, a new stimulus was presented. Reaction times to responding were recorded. Each N-back condition (1, 2, and 3-back) consisted of the presentation of 280 stimuli (Figure 22).

N-Back Task

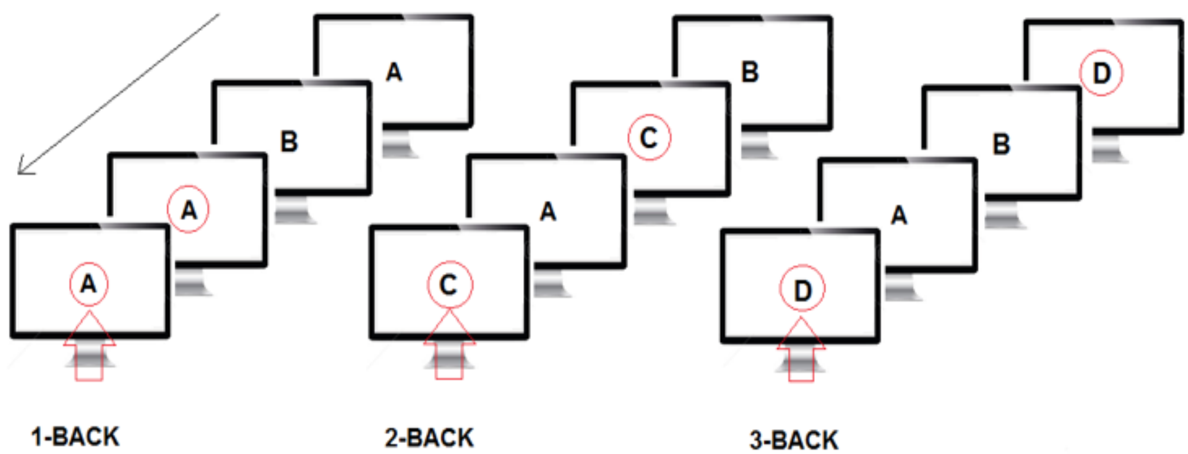


Figure 22. A) N-BACK Task: Visual illustration of the three levels of the N-back task. The red arrow indicates when the subject has been instructed to press the space key

7.4.2 Executive Functioning Data Processing

Data processing was performed in Matlab (Mathworks, Inc.) and EEGLAB (Delorme & Makeig, 2004). The raw EEG data was average referenced and down-sampled from 2048 Hz to 256 Hz. A high-pass filter at 1 Hz using an elliptical non-linear filter (IIR; transition bandwidth of 0.7 Hz and order of 6) was applied, and the data was then average referenced again. Extended Infomax Independent Component Analysis (ICA) was then used to identify ocular and muscle artifacts (Delorme et al., 2007). ICA components for eye blink, lateral eye movements and temporal muscle noise were identified and subtracted from the data by the visual inspection of both the component scalp topographies and power spectrum distributions. Between 1 and 5 artifactual components were removed for each subject. Bad electrodes (0 to 20 per subject, average of 6 per subject) and bad epochs containing paroxysmal activity were manually removed from the data.

7.5 Results I Neurofeedback Training

7.5.1 Statistical Results: Neurofeedback effects on Amplitudes (NF vs SHAM)

Here, using the General Linear Model, we calculated how theta power varied across groups (NFB vs Sham), by averaging the EEG activity across the sessions (1-6) for each day (days 1-8). We also included subject as factor that was hierarchically nested within Groups (because different groups contain different subjects). Including or not subjects in the GLM returned similar results although including subjects tended to increase significance. Notice that Group is the only categorical variable (subject is also a categorical variable but since it is nested within groups it is not possible to calculate the interaction with Group). Sessions and days are continuous variables. We are reporting the default Statistica analysis. We observe significant difference in theta between groups, and significant difference in theta between sessions (Table 2). Theta power was larger for the neurofeedback group (44.62 equivalent dB (20*log (mV^2)) compared to the Sham group (44.35 equivalent dB).

Neurofeedback training effects and baseline amplitudes are shown in Figure 23 for both groups. Statistical analyses using R software were used to perform a Pearson correlation test (Sham group: r^2 = 0.14, t = -0.99, df = 6, p-value = 0.36, neurofeedback group: r^2 = 0.49, t = 2.42, df= 6, p-value = 0.05). Our results show a significant correlation ($p < 0.05$; see Figure 22) for the neurofeedback group, while no significant relationship between the evolutions of FMθ for the sham group was observed. There appears to be an effect of neurofeedback training on the strengthening of FMθ resulting in increasing linear regression for the group receiving the actual neurofeedback (R^2 = 0.49). The regularity of the shape of the curve and of the growth during the sessions can be noted, contrary to the control group that presents a more heterogeneous and chaotic activity. We also observed significant effects in the EEG spectra over the training electrode site Fz, for both theta (3.5-6.5 Hz), low alpha (9-10 Hz) and beta frequencies (12 - 18 Hz) in the EEG spectral power using permutation statistics ($p < 0.05$; see Figure 24).

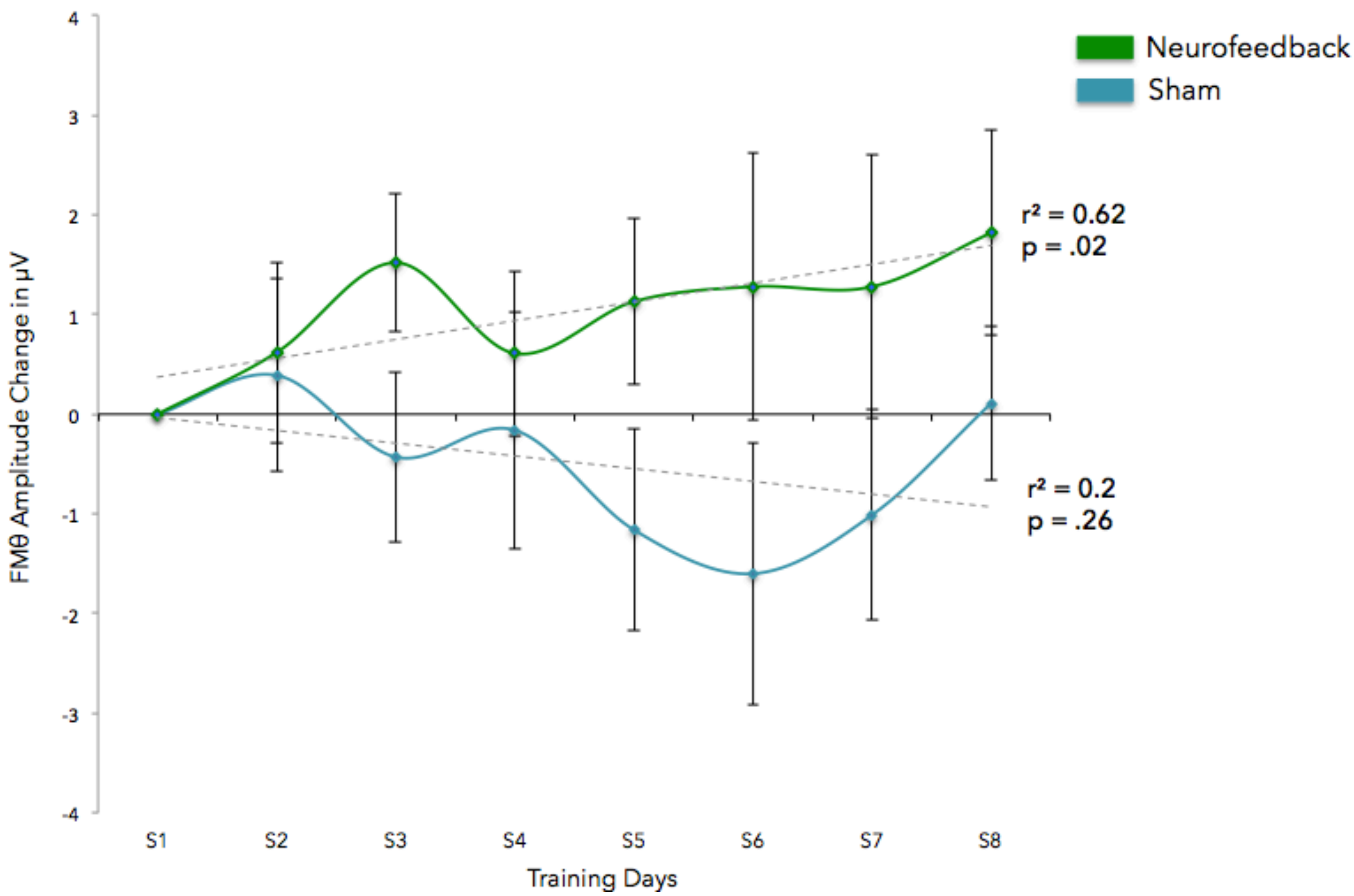
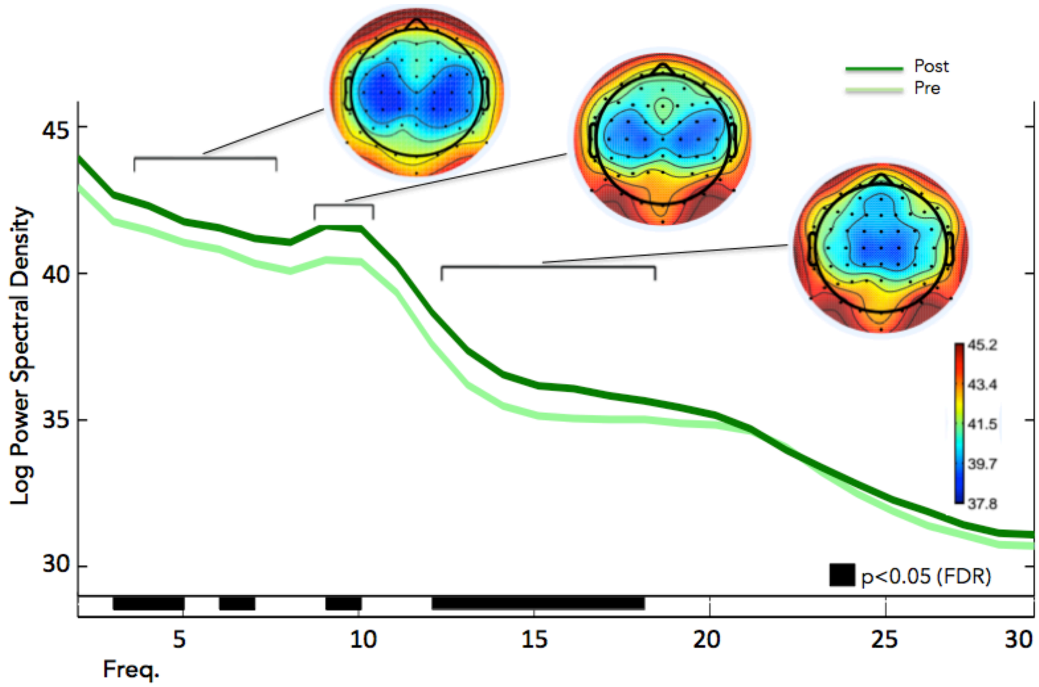


Figure 23. Neurofeedback FMθ Training Gain. This figure shows the enhancement across sessions, and reflects FMθ amplitude percent change for the mean of theta power for the Neurofeedback group (blue) and the Sham group (red) across each training session (S1-S8) as averaged over all corresponding blocks (blocks 1-6) as compared to the first session (S1). Baseline amplitude changes are reflected by the dotted lines for each group respectively, and are shown for the training relative to the first baseline measurements. Error bars indicated the standard error of the mean.



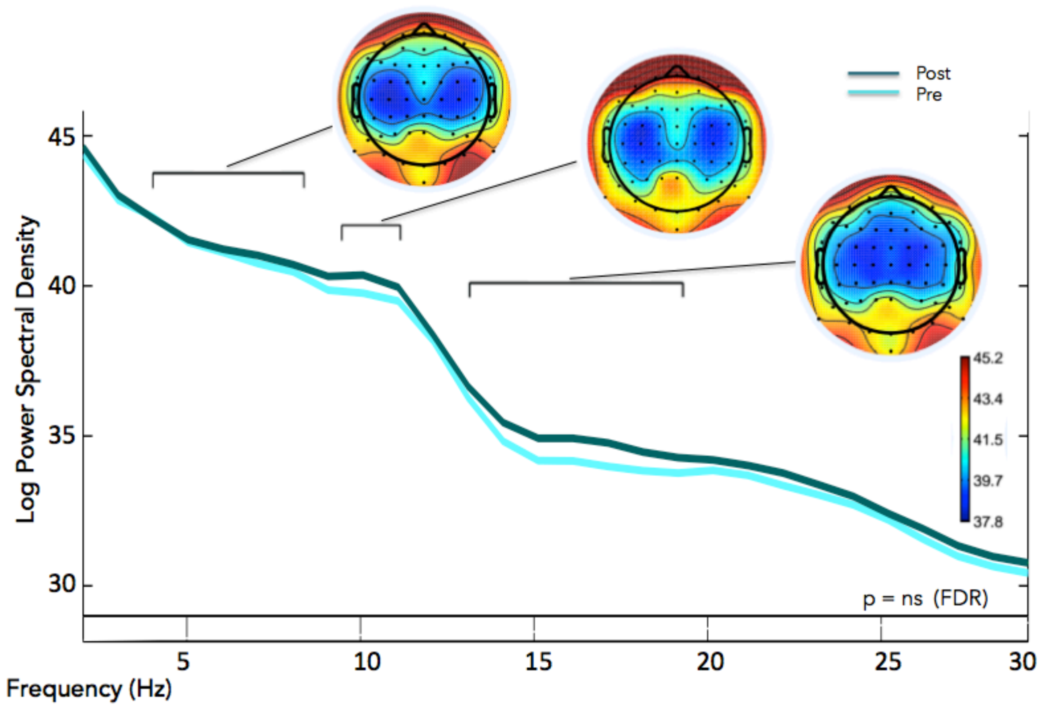


Figure 24. Frequency Spectra for the Feedback group (top) and Sham group (bottom) showing differences in averaged spectral power between Session 1 as compared to Session 8 for electrode Fz (feedback location). Significant differences in multiple frequency bands were observed for the Feedback group (p < .05, corrected for multiple comparisons) (reflected as black bars above the x-axis) but not for the Sham group.

7.5.2 Statistical Results on N-back Task

GLM analyses were performed on the number of correct responses and reaction times. We choose to run this complex model rather than a collection of simpler ones (like a t-test on Group on a variety of sub conditions) to avoid the problem of having to correct for multiple comparisons. In addition the GLM allows capturing all the subtleties of the data and provide an overarching view of all the effect at once without having to run multiple analyses. As was done for the neurofeedback data, each subject is added as a factor that is hierarchically nested within groups (however removing these factors does not dramatically affect the results). For the number of correct responses, we observed a significant effect of the condition (1, 2, 3 back), session, and response (type of response), which is logical given that there are more correct responses for 1-back than for 2 back and more correct responses for 2 back than for 3 back. Condition by response is significant indicating an effect of the condition (1, 2 or 3 back) on the number of hit and true negative (Table 3).

Table 3. Statistical results of the GLM analysis for the number of correct responses.

Nback- Correct Response	F	p	DF
Intercept	9411.69	0.0000	1
Group	0.36	0.5516	1
Condition	127.36	0.0000	2
Session	8.60	0.0037	1
Response	900.74	0.0000	2
Group*Condition	0.84	0.4319	2
Group*Session	0.14	0.7136	1
Condition*Session	1.68	0.1891	2
Group*Response	2.00	0.1582	1
Condition*Response	17.82	0.0000	2
Session*Response	3.74	0.0544	1
Group*Condition*Session	0.05	0.9542	2
Group*Condition*Response	2.43	0.0904	2
Group*Session*Response	0.39	0.5356	1
Condition*Session*Response	0.19	0.8286	2
2*3*4*5	1.34	0.2638	2
Subject (Group)	2.78	0.0001	22
Error			242

GLM analyses on the reaction times revealed a significant interaction effect for the session (pre vs. post), showing reduced reaction times for correct responses on the n-back for participants in the NFB group as compared to the Sham feedback group after the training (Figure 24).

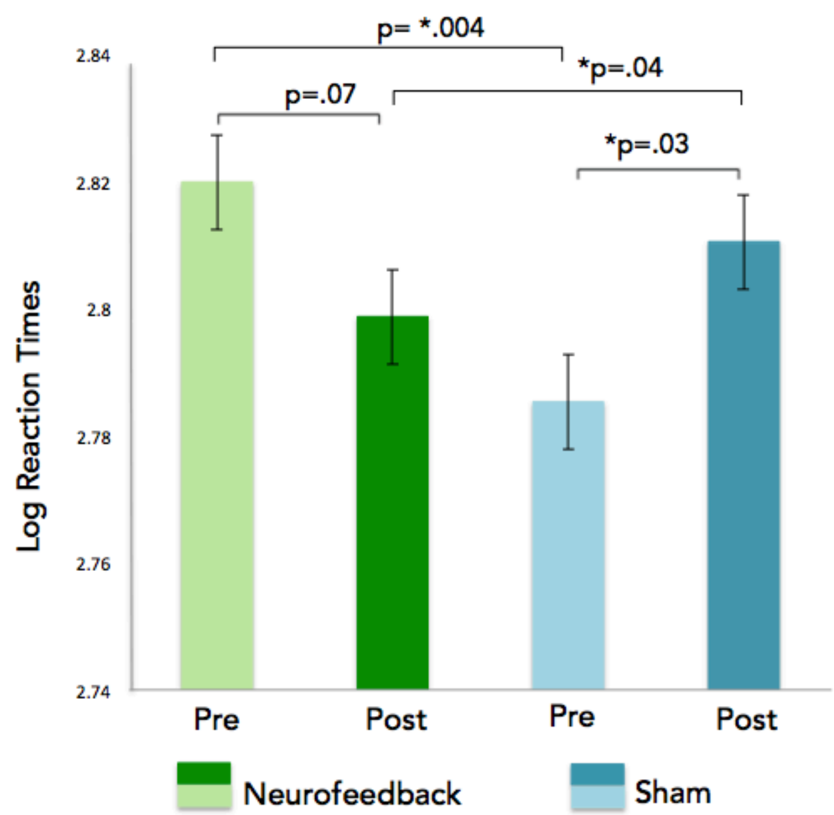


Figure 24. Log reaction times for the N-back task before and after training. The GLM revealed an interaction effect for reduced reaction times in the Neurofeedback group for correct trials as compared to the Sham group.

7.5.2.1 EEG activity in the N-back task

An increase in alpha power after training was observed for the 2-back condition (Figure 25) We also observed a significant difference in gamma power (p <0.01) around the prefrontal and left temporal parietal area in the 2-back condition for subjects who received neurofeedback (Figure

26), however no interaction effects were observed between neurofeedback and sham subjects. A more rigorous analysis will be done to assess the non-artifactual nature of the activity.

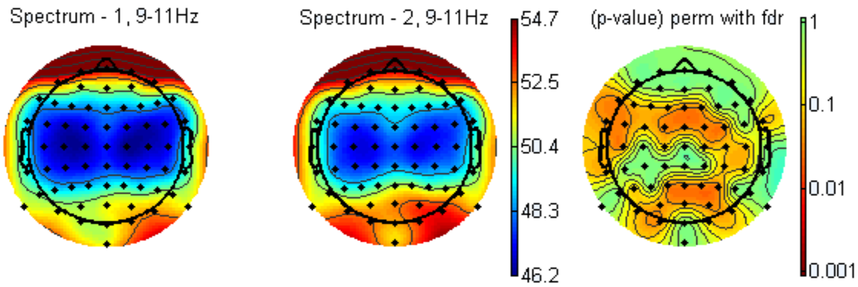


Figure 25: Results for alpha power after grouping the two groups for the 2-back condition before training (left) and after (right). Color bar on the right shows the significance of the pre and post difference after corrections for multiple comparisons.

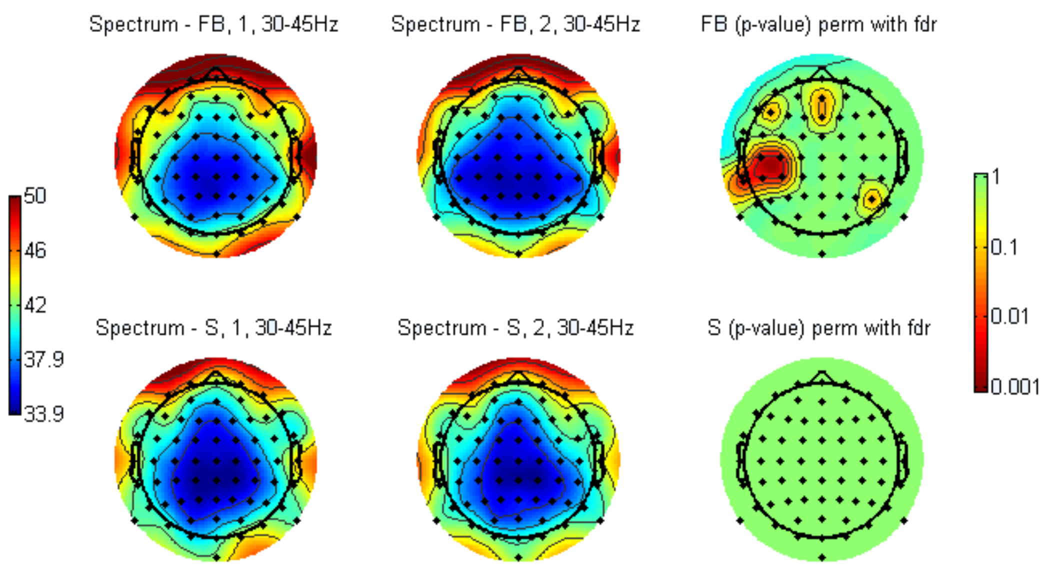


Figure 26: Results for the Neurofeedback (top) and SHAM (bottom) groups for gamma-power during the 2-back task, before (left) and after (middle) the neurofeedback sessions. Colorbar on the right shows the statistical significance of the difference pre and post neurofeedback.

7.6 Discussion

7.6.1 Trainability of FMθ

Here we found a significant, linear increase of FMθ amplitude with consistent effects across sessions. As has been found in previous neurofeedback studies, several of our neurofeedback participants were unable to intentionally increase FMθ amplitude. The findings presented in this study suggest that it is possible to train and reinforce the networks generating FMθ activity measured at electrode Fz through a neurofeedback training protocol in which subjects used techniques such as focused breathing, relaxation and visual concentration on the color fluctuations in the feedback. Participants in our neurofeedback group showed a significant increase in FMθ activity across sessions as compared to controls. To our knowledge this is the first study to test the feasibility of neurofeedback training based on the implementation of meditation strategies, as well as for a specific frequency band and location based on findings from advanced meditations practitioners. Enriquez-Geppert and colleagues (2013) implemented a similar neurofeedback protocol of an eight-session FMθ neurofeedback training, however their study differed on several key points. First, they provided different types of strategies such as mental operations, emotions, imagination, memories, and thoughts of movements, strategies that resemble a form of intentional mind wandering. An interesting possibility is that some of the cognitive mechanisms involved in intentional mind wandering may rely on similar cognitive control mechanisms that are trained during meditation practice, with FMθ reflecting intentional and guided cognitive effort. While the FMθ trained in the study by Enriquez-Geppert and colleagues was based on an individualized theta peak (~5Hz) determined by a series of cognitive tasks for each subject, we chose to provide feedback based on a broader theta range, as the cognitive control trained during methods and techniques such as meditation may reflect the cooperation of several different neural generators across the frontal cortex, each with potentially differing and preferred spectral peaks within the theta band.

7.6.2 Responders and Nonresponders

The presence of subjects who were not responsive to the neurofeedback training falls in line with many previous neurofeedback studies that have reported non-responsiveness to NF. Here, we identified approximately 25% of participants (3 participants) who showed a negative response and linear slope across training sessions (Figure 27). These statistics align with previous observations made in earlier studies (Zoefel et al., 2011; Lubar et al., 1995). While both groups in our study reported enthusiasm and a sense of agency in controlling the feedback, several sham

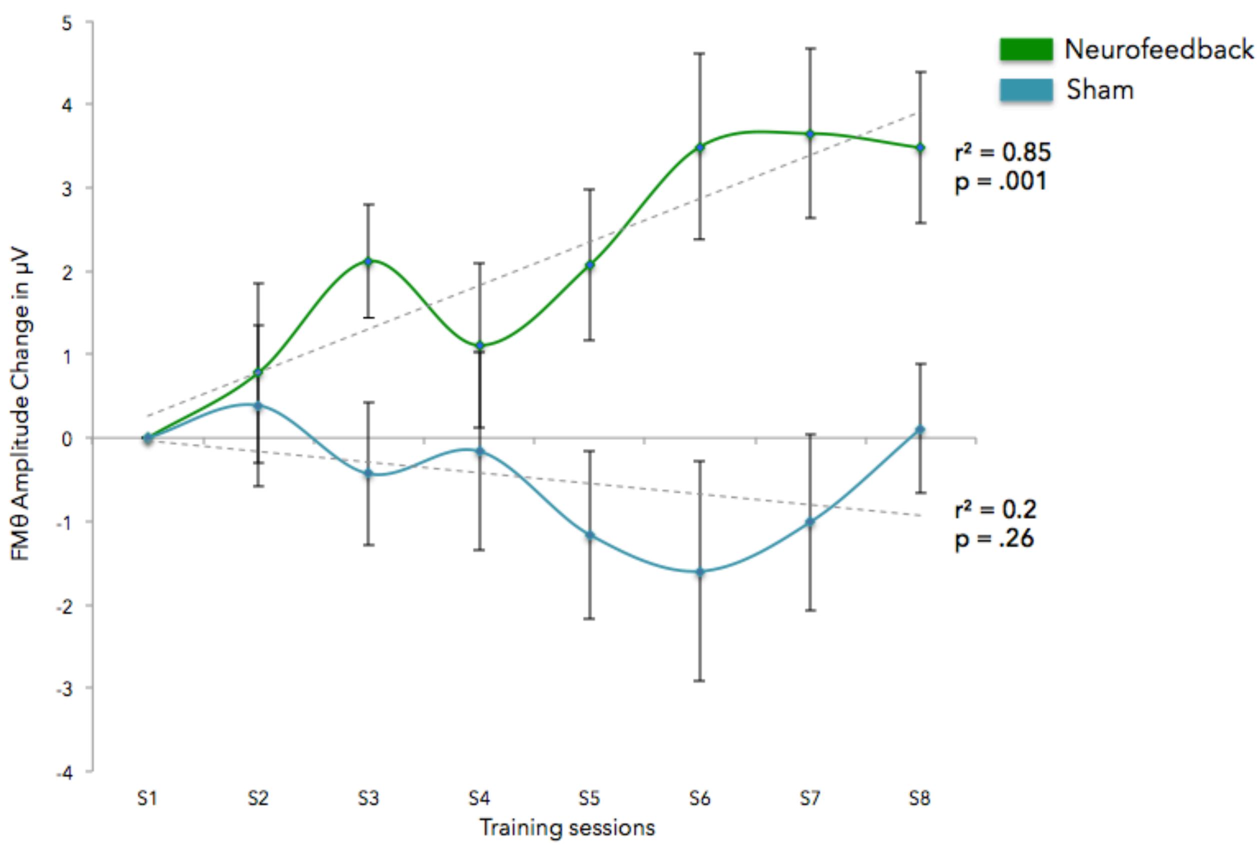


Figure 27. This figure illustrates the differences in training gain between subjects who were responsive to the neurofeedback versus those who were not (see discussion). FMθ amplitude is shown for each training session (S1-S8) and reflects the average of all corresponding blocks (block 1-6) relative to the first training session (S1) separately for responders and non-responders in percent change. Error bars reflect the standard error of the mean.

alternative explanation for non-responders is the use of inappropriate and ineffective strategies unrelated to the cognitive processes involved in the generation and modulation of FMθ waves. In subjects reported an increased sense of task difficulty as based in their daily logs. Therefore lack of motivation is most likely not the cause of their respective non-responsiveness. Another this way, they may fail to modify the interface of neurofeedback and do not realize learning during the sessions because they are incapable of taking advantage of the feedback which subsequently allows for the refinement and modulation of brain activity. While this explanation may be viable, it should be noted that our 3 non-responding subjects all reported finding relevant strategies (visually focus on one point of the screen, focus on breathing) within the first several sessions.

Research investigating the effects of cognitive and behavioral trainings have found that regional differences in brain structure and connectivity have been linked to predictability of training effectiveness in complex cognitive tasks and language learning (Basak, Voss, Erickson, Boot, & Kramer, 2011; Erickson et al., 2010; Flöel, de Vries, Scholz, Breitenstein, & Johansen-Berg, 2009; Loui, Li, & Schlaug, 2011; Wong, Chandrasekaran, Garibaldi, & Wong, 2011). In a separate, follow up paper by Enriquez-Geppert and colleagues (2013) they found that inter-individual variations in MCC structure and cortical fissuration predicted the success of FM neurofeedback training. The anatomical aspect of the current study was incorporated to address these potentially mediating variables of successful training, and to investigate the possibility of FMθ training to potentially facilitated new synaptic connections. This study will explore this possibility by examining the anatomical substrates of FMθ oscillations.

7.6.3 Inclusion of an active control group

Throughout the history of Neurofeedback research, one of the most central points of criticism has been the omission of appropriate control groups (Gevensleben et al., 2009; Gruzelier & Egner, 2005). While many protocols control for practice and repetition effects through the use of passive control groups, many additional effects may play a pivotal roles in the success of training, such as expectancy and placebo effects, which have been linked to improvements in clinical drug study outcomes (e.g., Price, Finniss, & Benedetti, 2008). Another potentially mediating factor in neurofeedback studies may be the exposure to the visual feedback itself. Given that we observed some changes in the sham group as well, this study underlines the importance for adequately controlling not only for repetition-related but also for such non-specific effects.

7.6.4 Neuroanatomy of FMθ

As discussed previously, interindividual differences and the degree of MCC fissurization has been linked with behavioral differences, as well with neuropsychological functioning during tasks measuring executive functions (Huster, Wolters, et al., 2009; Huster, Enriquez-Geppert, Pantev, & Bruchmann, 2014; Huster, Westerhausen, & Herrmann, 2011). Differences of MCC fissurization may account for interindividual differences in the topography and robustness of FMθ, and may be associated with an individual's ability to modulate this oscillation (Enriquez-Geppert et al., 2013). These variations have been linked to differences in executive functions (Huster et al., 2009, 2014, 2011; Huster, Westerhausen, Kreuder, Schweiger, & Wittling, 2007; Huster, Enriquez-Geppert, Lavallee, Falkenstein, & Herrmann, 2013). Enriquez-Geppert and colleagues (2013) hypothesized that the neuroanatomical structure, and high concentration of convolutions could very well play a role in the different results observed during the reinforcement of FMθ neurofeedback. They found that increases in FMθ power measured during the initial training sessions predicted the success of the FMθ increase across the eight sessions of training, while pre-existing inter-individual differences in the morphology of the right MCC, as well as higher white matter concentration of the right and larger volumes of the left cingulate bundle were associated with stronger FMθ enhancement during initial training success. However we observed no significant correlations between increases in FMθ power measured during the first session when compared with their total increase of FMθ power after the eight training sessions.

7.6.5 Changes in cerebral structures by neurofeedback

While recent findings now show that there are specific neuroanatomical criteria that can predict neurofeedback training success, it remains relatively unclear as whether these types of focal training protocols stimulate cerebral plasticity. While the MRI data will not be included in the present dissertation as it will be analyzed a later date, a key part of this study will examine the structural and functional characteristics before and after the training. Additionally, we will investigate these data using voxel based morphometry, changes in gray and white matter volume and concentration, in addition to incorporating specific individual characteristics of the cingulate cortex, such as the occurrence of a second cingulate gyrus, and its direct relationship with training success, as has previously been suggested (Enriquez-Geppert, Huster, Scharfenort et al., 2013; Huster et al., 2011). FMθ modulation may be directly linked to and dependent on the specific morphology of MCC neurons, white matter characteristics such as increased bundle volumes, axonal density, or myelination are thought to ease the interregional synchronization of FMθ oscillations (Cohen, 2011). These measures will be assessed in our diffusion tensor imaging (DTI) data.

7.6.6 Enhancements in Executive Functioning

Significant differences were observed in our Neurofeedback group who showed reduced reaction times in the N-back task on correct trials following the two-week neurofeedback training. While this effect is impressive given the short duration of the experimental protocol, we observed no other significant effects in regards to improved task performance. It is important to consider that any study implementing a pre-post design can expect repetition-related effects (these are effects that arise from simply repeatedly testing a task). Such unspecific repetition-related effects are particularly well known in behavioral training studies and are found in all subjects (Karbach and Kray, 2009; Schneiders et al., 2011). Mid-frontal theta phase synchrony had been observed between the MCC and distal brain regions in Cohen and Cavanagh (2011), who found that during conflict monitoring, reaction times modulated single-trial phase synchrony between the MCC and lateral prefrontal. The relationship between behavioral task proficiency and neural activity may not necessarily be linear in pre-post training protocols given that complex interactions of repetition-related performance changes, training-induced changes in neural responding and behavior, and task difficulty may exist.

7.6.7 Optimizing neurofeedback protocols

The exploration of training effects of different long-lasting training lags (from minutes up to several days) on a systematic level is important concerning at least two aspects, namely with respect to the investigation of neuronal correlates, and in regards to finding the optimized repetition interval for neurofeedback training protocols. The anatomical MRI and functional

MRI data collected may potentially provide new insight into the refining of FMθ training protocols. Our study showed successful modulation of FMθ training by means of an eight-session scalp EEG neurofeedback protocol, through the use of strategies which encouraged focused breathing and concentration techniques, while having accounted for several historically unspecified effects such a reliable control group, and strictly controlled time lags.

Part III

Chapter 8: General Discussion

8.1 An overview of the results and general discussion

In the 1990's Francisco Varela proposed the methodologies of Neurophenomenology as a path of reconciliation for addressing the hard problems of consciousness (Varela, 1996). Over the last 20 years we have seen a concerted effort to reintegrate first person accounts of subjective experience into methodologies in fundamental neuroscience. In this thesis, I related the neurophysiological features and data to the phenomenological nature of experience through methodologically novel and rigorous methods. These findings contribute to our understanding of some of the subtle relationships between phenomenological experience and the corresponding and potentially causal effects on neural activity. However much work remains.

8.2 Reduced mind wandering in advanced meditation practitioners

8.2.1. General Findings

In our first study, we observed significant differences in both the theta and alpha EEG activity of experienced meditators while absorbed in meditation as compared to mind wandering. This study also provides some of the first behavioral evidence that meditation expertise is associated with an attenuated frequency of mind wandering, suggesting that meditation training reduces the susceptibility of the mind to wander, subsequently leading to longer periods of meditative absorption. The observed modulations seen in FMθ suggest a functional relationship between the sources contributing to our observed FMθ activity and the broader frontoparietal control network involved in maintaining top-down representations of goal states, learning and directed attention, and add to an expanding body of literature suggesting that meditation training may modulate some of the neural mechanisms involved in cognitive control and attention. Our study also provides new evidence to support the claims posited by Spreng & Schacter (2012) that both internal and external orientations of focus may be facilitated via common neural mechanisms, with our findings suggesting that meditation training may target the neural substrates underlying these oscillations. The observed increase of alpha activity in our expert meditation group supports its putative role in the processing and integration of somatosensory information (Kerr et al., 2013; Whitmarsh et al., 2014), as well as its role in mediating cognitive entrainments, and provide further evidence that meditation training may modulate cortical mechanisms underlying somatosensory perception. Furthermore, our findings provide additional support for theories that suggest that the enhanced integration of the neural activity underlying sensory information and attention can be trained and modulated via top-down mechanisms.

8.2.2 Enhanced metacognitive accuracy and sustained attention

The findings from our study are particularly notable given that our meditation practitioners were practicing a form of mantra meditation, in which they repetitively recite a mantra (mantras are composed of a series of words or beej sounds; see section 5.2.2). The repetition of a mantra may share functional commonalities with the generation of inner speech, a common feature of mind wandering (Stawarczyk, Cassol, & D'Argembeau, 2013). Thus, these findings may provide insight into the delineation of specific neural differences between intentional, aware, and directed forms of cognitive activity, as compared to unintentional spontaneously generated thought. Given that all of the participants in our study were extensively trained in these meditative techniques, were motivated to participate in the study, and that the primary goal of meditation is take note of when the mind wanders and bring attention back to the mantra or breath, the mind wandering observed in our advanced practitioners most likely reflects a form of unintentional mind wandering. While that would suggest that advanced meditators still unintentionally mind wander, the attenuated frequency of mind wandering trials as compared to the novices suggests two possible outcomes. The first would be that that meditation practice and experience facilitates improved accuracy in the evaluating of ongoing mental activity and the reporting of neurophenomenological data. The second is that practitioners are capable of longer periods of sustained meditation as a consequence of practice, therefore strengthening the neural mechanisms underlying sustained attention. While the current paradigm is not capable of deciphering between these two factors, it does however provide some of the first direct evidence supporting the idea that meditation expertise leads to specific behavioral changes and that these changes can be measured not only neurophysiologically, but behaviorally as well.

While our research findings would seem to suggest that over time meditation practice may reduce the overall frequency of spontaneous thought, this may additionally be influenced by the ability to actively identify and disengage from mind wandering and subsequently reorient attention. It may also be the case that meditation practice facilitates the unification of various attentional mechanisms so as to moderate mind wandering. Future avenues of research on mind wandering and meditation training should focus on further disentangling whether meditation increases the metacognitive awareness of mind wandering and the subsequent reorientation of attention, if meditation enhances a fundamental capacity of allocating attentional resources, or if meditation facilitates an overall reduction in the occurrence of mind wandering events, as our findings suggest.

8.2.3 Novelty of the experiment design

Our implementation of a probe-caught mind wandering paradigm was based on previous findings which suggest that the probe-caught method reflects the true frequency of mind wandering episodes, whereas mind wandering that is self-reported may reflect an individual's metacognitive awareness of mind wandering (Smallwood & Schooler, 2006). While meditation practice may increase the number of self-caught mind wandering episodes over time by enhancing metacognitive awareness of internal experience, it may also improve the accuracy with which one is able to retrospectively label and identify whether they were fully engaged in the meditation, partially engaged in the meditation, or mind wandering and not engaged in the mediation at all. On the other hand, due to their lack of extensive training in the continual and subtle observation of mental states novice practitioners may be less apt at accurately identifying and reporting with accuracy the mental activity in the time period preceding the sampling probe.

Collectively, these findings suggest that variations in reports from both self- and probe-caught mind wandering paradigms should be mutually considered in future experience sampling studies when investigating differences in the brain activity associated with probe- vs self-caught mind wandering, as well as when comparing mind wandering and meditation.

The use of first person experience to evaluate the ongoing mental activity and report the experience based on a graded scale of 'depth' leads to several challenges in the processing of the EEG data. The use of phenomenological data to drive EEG analysis is challenging due to large interindividual differences in strategies implemented for identifying and labeling mental states. Whereas some of our subjects refrained from using any depth above 1, others report only higher depths (2 and 3) of meditative absorption. This may have been further confounded by the fact that based on the need for a sufficient number of trials; subjects were probed throughout their meditation approximately every 3 minutes. While the majority of practitioners reported that this did not hinder their ability to engage in their practice, future studies implementing similar designs should allow for longer periods of time to pass to allow subjects to enter into deeper meditative states. Furthermore, whereas we implemented a scale based on a 0-3 range, 0 reflecting being not engaged in that state at all, and 3 reflecting complete immersion (e.g. deeply immersed in meditation), a larger scale may allow for a more nuanced assessment of their respective states.

8.2.4 Expanding upon a more nuanced view of mind wandering

The study by Killingsworth and Gilbert (2010) found evidence suggesting that people are engaged in thoughts unrelated to the task at hand ~50% of the time, however, the larger picture is far more nuanced. Based on the findings presented in Chapter 5, we have discussed why and how this abundance of mind wandering plays an essential role in memory formation, the prioritization of current concerns, creativity, how it can be intentional or unintentional, constructive, or ruminative. Since the process of thought seems to be largely spontaneous and uncontrollable, one of the main questions we sought to answer in this thesis was whether there are methods of increasing the awareness of, flexibility and diversity of these spontaneous chains of thought. Although cognitive psychologists and researchers investigating the role of mind wandering and spontaneous thought have been addressing this question for several decades now (Singer & McCraven, 1961; Singer, 1966), it would seem that we are only just beginning to seriously apply the necessary scientific scrutiny to such "spontaneous" thought processes (Andrews-Hanna, Smallwood, & Spreng, 2014; Fox et al., 2014, 2015; Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015; Smallwood & Andrews-Hanna, 2013).

Recent findings have begun to disentangle some of the subtleties involved in mind wandering, which have thus far used either self-report or spontaneous probes to measure mind wandering. However, the methods have not addressed the degree with which the minds that are wandering are doing so with or without intention. These important differences seem to have evaded existing methodologies and paradigms, and may have fundamentally distinct underlying mechanisms when viewed from a framework of distinguishing between exogenous and endogenous precursors (Seli et al., 2016). Interesting findings by Baird et al. (2011) suggest that focusing on future thoughts during mind wandering episodes may facilitate a functional role for mind wandering in problem solving, however, it remains unclear as to whether the kind of mind wandering (intentional vs. unintentional) plays a mediating role. As highlighted in the work presented in this study, enhanced metacognitive abilities cultivated through practices such as meditation may very likely influence the accuracy in detection and awareness of mind wandering, and potentially influence specific types of mind wandering (intentional vs. unintentional) when it occurs. Perhaps through meditation training, one can learn to optimize mind wandering by being intentionally engaged in the process and learn to play a more active and constructive role. Given the previous findings that have shown an increased negative affect during periods of mind wandering, regardless of content, these findings may suggest that individuals generally prefer to experience a sense of agency and feel engaged in their thought processes, rather than being taken captive by them. It is clear that meditation practitioners possess great potential to provide insights into the nature of spontaneous thoughts and mind wandering.

8.3 Investigating FMθ neurofeedback

8.3.1 General Findings

An accumulating body of literature supports the notion that attention-sensory regulation and the enhancement of brain function via neurofeedback is feasible, and that it may enhance self-regulatory capacities applicable to both clinical and societal contexts. Here, through the implementation of a neurofeedback paradigm based on a specific frequency range (3.5- 6.5 Hz FMθ) and topography (Fz) that was observed in advanced meditation practitioners during concentration meditation (Brandmeyer and Delorme, 2016), we aimed to train this particular neural activity in normal participants. Having developed a new and novel paradigm that implemented meditative strategies such as focused breathing and alert meta-awareness of mental activity, our results suggest that these techniques were effective in facilitating the participant's real time modulation of FMθ EEG data through their direct, first person, subjective and conscious experience. While this method for regulating neurofeedback may be considered quite challenging for individuals without any prior meditation experience, previous findings have shown that self-regulation can be accomplished during neurofeedback without highly cognitive, explicit, and or conscious strategies, as evidenced by primate and rodent research on associative learning and operant conditioning (Koralek, Jin, Long Ii, Costa, & Carmena, 2012; Fetz, 1969). Our findings suggest that it is possible to up-regulate FMθ using meditation inspired strategies in an eight-session neurofeedback paradigm. We also observed differences in alpha and beta frequency bands in the same topographic training location (electrode Fz), findings consistent with previous research suggesting that there may be a somewhat non-specific effect when implementing neurofeedback training via scalp-EEG. In our preliminary analysis of the results on the pre and post executive tasks, we failed to find any transcending effects.

8.3.2 Supporting findings and an overview of future analyses

Corlier et al. (2016) demonstrated in an elegantly designed intracranial study that FMθ could be modulated with precise spatial and frequency specificity. They found that several critical parameters, namely power, amplitude, synchronization, and phase locking, could be used to track important changes across training sessions. They suggest that shifts in these parameters between the first and the last sessions may not be progressive or linear, and that when high degrees of phase-amplitude coupling are present, a frequency range that has not been the target of neurofeedback training will be influenced by the same strategy when tested directly. Thus, the non-specific changes we observed in both the alpha and beta frequency bands may have been due to a high degree of phase coupling. These analyses will be conducted in our future manuscript for publication.

They additionally found that individual training performance correlated proportionally to the presence of FMθ before the neurofeedback training, suggesting that pre-existing interindividual differences directly influence the ability to voluntarily modulate this oscillatory rhythm. With a few exceptions (Enriquez-Geppert, Huster, Scharfenort, et al., 2014; Enriquez-Geppert, Huster, Figge, et al., 2014; Kotchoubey et al., 1999; Neumann & Birbaumer, 2003; Weber, Köberl, Frank, & Doppelmayr, 2011) these structural-functional differences have received surprisingly little attention, which is particularly notable given their ability to potentially predict and explain non-responsiveness to neurofeedback. FMθ oscillations have been linked to the recruitment and synchronization of midcingulate neuronal activity, whose numbers are associated with regional volume and gross-morphology (Cavanagh et al., 2012). These mechanisms are thought to facilitate the information integration occurring in the MCC, which has been shown to functionally interact with other cortical and subcortical areas via FMθ oscillatory activity (Cavanagh et al., 2012; Cohen, 2011). Previous studies have demonstrated that the MCC structure shows a large amount of gray and white matter volumetric variability across subjects, in addition to the local gyrification of regional microstructures (Fornito et al., 2004; Huster, Westerhausen, Kreuder, Schweiger, & Wittling, 2007, 2009; Yücel et al., 2001). Differences in gyrification have been shown to have functional significance (Welker, 1990), and are greatly influenced by neural connectivity (Caviness, Filipek, & Kennedy, 1989), and the existing underlying cytoarchitecture (Watson et al., 1993). Neuropsychological functioning and behavioral differences in executive tasks have been associated with the degree of midcingulate fissurization, with subjects who had leftward MCC folding asymmetry showing increased electrophysiological reactivity in tasks recruiting cognitive control (Fornito et al., 2004; Huster, Wolters, et al., 2009; Huster et al., 2014; Huster, Westerhausen, et al., 2009).

Additionally, research by Halder et al. (2013) reported that deep white matter structures were correlated with BCI-performance, with characteristics including white matter, increased bundle volumes, and axonal density, thought to enhance and enable the interregional synchronization of FMθ (Cohen, 2011). The only other previous study investigating FMθ modulation by Enriquez-Geppert and colleagues (2014) found that larger volumes of white matter in the right MCC, in addition to larger volumes of the left cingulate bundle were predictive of subjects abilities to enhance FMθ within sessions, however these measures could not predict lasting effects across the eight session training. They hypothesize that there may likely be other more important regions involving executive functions, learning, and memory related to the training increases and maintenance, with some of the different aspects of neurofeedback training associated with morphological differences in diverse functionally specialized brain structures. For example, individual differences in FMθ power may potentially reflect a larger number of neurons in the MCC, as well as variations in the number of synaptic connections, dendritic or axonal branching, and vascularization all can lead to differences at the functional level (Enriquez-Geppert et al., 2013). We plan to explore these analyses in our DTI and EEG data.

Additional evidence suggests that neurofeedback training can be used to increase cortical excitability (Ros, Munneke, Ruge, Gruzelier, & Rothwell, 2010), induce hebbian plasticity (Lisman, 1989), and that self-induced repetitive induction of oscillatory activity increases neuron to population synchrony, strengthening and reinforcing existing circuitry (Markram, Lübke, Frotscher, & Sakmann, 1997). Buzsáki (2004) has proposed that long-term potentiation (LTP) is particularly sensitive to the phase of theta oscillations, proposing that they serve as a window for facilitating memory formation. Additional EEG analyses will further examine the effects of training on additional executive functions including response inhibition (SART Task) and conflict detection (Local Global). The MRI and DTI data that was collected before and after the neurofeedback training sessions will examine the potential network reconfiguration and anatomically connectivity to assess whether changes in connectivity are directionally related to changes in the functional networks.

8.3.3 Unaccounted for factors and limitations of study

Additional interactions between outside factors such as sleep and exercise may highly impact the effectiveness of cognitive training protocols. Factors such as exercise have been shown to stimulate the new growth of stem cells in the hippocampus, with research showing enhanced optimization of new cellular structures when simultaneously paired with cognitive training measures (Shors, Anderson, Curlik II, & Nokia, 2012; Shors, Olson, Bates, Selby, & Alderman, 2014; van Praag et al., 2002). Studies comparing the effectiveness of mindfulness protocols that were paired or not paired with an exercise regimen found that participants who participated in the exercise intervention had highly significant improvements in various cognitive measures as compared to subjects who just received the mindfulness training (Shors et al., 2014). The direct relationship between neural plasticity and sleep has also been shown to play a key role in cognitive training effectiveness. Research has shown network wide reactivations of the (same) neuronal assemblies during sleep that have been recently involved in new and challenging environmental circumstances. These activations are presumably linked to the re-processing of memory traces during sleep. Post-training sleep deprivation has been found to significantly impair subsequent performance on various tasks, both in animals and humans. Additional research has shown an increase in REM sleep following training in several experimental conditions, and that this increased REM effect goes away after a given task has been mastered (Poe, Nitz, McNaughton, & Barnes, 2000; Roozendaal, 2000). In the current study, we did not assess the number of hours of sleep for each preceding night and are therefore unable to explore whether or not the training gain effects were in any way correlated with sleep duration or quality. Additionally, we did not evaluate the motivation of subjects in a quantitative manner. While we did have subjects write down what they were experiencing, and how they felt after each session, we did not use a scale by which subjects could be objectively compared. Future studies should incorporate these measures.

8.4 The path forward

At present, neural oscillations and amplitude can be modulated by means of neurofeedback (EEG, iEEG) and a variety of forms of neurostimulation including transcranial magnetic stimulation (TMS), transcranial direct-current stimulation (tDCS), transcranial alternating-current stimulation (tACS), transcranial ultrasound (TUS), and transcranial focused ultrasound (tFUS). A relatively new method, tFUS may hold great promise in the modulation of human brain circuit activity and global brain mapping efforts, as well as for the diagnostic and therapeutic applications in neuroscience due to its highly refined spatial resolution and precision (Lee et al., 2015). One study found that tFUS beams aimed at S1 could 'focally modulate short-latency and late-onset evoked cortical activity elicited in humans by somatosensory (median nerve) stimulation that enhanced the somatosensory discrimination abilities of volunteers (Legon et al., 2014). While methods such as these present many intriguing and exciting new avenues of research, one advantage of neurofeedback protocols is that they require the continuous involvement of the participants during the training (i.e. operant conditioning), a process that may prove to increase the efficiency of long-term retention and encoding, as has been discussed in various constructivist learning theories (e.g., Narli, 2011). Furthermore, self-efficacy may be enhanced through the positive experience of successfully modulating continuous feedback, wherein the bidirectional relationship between the recorded data and the subject is inherently causal (Carlson-Catalano & Ferreira, 2001; Linden et al., 2012).

One of the fundamental challenges that individuals experience when learning to meditate is the unceasing propensity of the mind to wander, and the frustration associated with the lack of awareness of when this occurs. Novice meditators may often find themselves discouraged after realizing that they had spent the majority of a meditation session unaware that they had been engaged in mind wandering. While the development of metacognitive awareness is a fundamental step in learning to practice meditation, and these experiences ultimately help individuals learn to recognize mind wandering during daily life, even the Dalai Lama has stated that he believes technologies that aid and assist in promoting and training meditation are ultimately beneficial. A study by deCharms and colleagues (2005) suggest that feedback is essential information for enhancing self-regulatory capabilities. In a study on chronic pain patients, they demonstrated that the feedback of neural activity was predictive of success in controlling the neural processing behind pain perception, subsequently reducing perceived pain. One would assume that pain patients already have continuously available sensory feedback of their pain level based on their personal and direct experience, in addition to a strong motivation to restrain the pain intensity. Nevertheless, the personal pain perception alone was not sufficient for the control of pain, whereas the feedback on neural activity seemed to provide additional information that played a crucial role in the ability to control physiological processes. These findings provide support for new applications and advanced wearable technologies that are coming onto the market, some with surprising high quality EEG signal detection (emotiv, OpenBCI, the MOVE system). While systems aim to assist and train the regulation of various physiological or cognitive activities such as sleep (Dreem) and lucid dreaming (iBand), mood regulation (Thync), and athletic performance (Foc.us, Quantified Self), other new technologies can help individuals who are physically handicapped (Tools for Brain-Computer Interaction; TOBI) or have clinical disorders, such as epilepsy (Neuronaute). While these advanced technologies will undoubtedly be widely distributed and integrated into the lives of millions in the not so distant future, it is essential that neuroscientific research studies provide reliable and sound protocols that can take advantage of the rapidly advancing technological sector.

While direct phenomenal experiences are accessible only to an individual, new methods such as those developed by Petitmengin & Lachaux (2013) enable the use of subjective feedback of neural and experiential dynamics at an incredibly refined level. BrainTv, developed by Lachaux, responds to that question by giving subjects instantaneous feedback (such as an image or sound) and takes into account both the subjective data of the individual and objective data of the recordings simultaneously, facilitating a direct comparison process capable of finding correlative relationships (http://www.braintv.org; Petitmengin & Lachaux (2013)). This approach uses intracranial EEG recordings in epileptic patients, displaying real-time activity recorded at particular cortical locations in several frequency bands, including alpha (8–12 Hz), beta (12–30 Hz), and gamma bands (>40 Hz; Lachaux et al., 2007). These microdynamic approaches to neurofeedback may allow us to glimpse the process of co-constitution of subject and object (Lutz & Thompson, 2003; Petitmengin & Lachaux, 2013; Varela, Thompson, & Rosch, 1991), and give both methodological answers to issues surrounding the correlation between experiential and neuronal, first person and third-person descriptions of our cognitive processes. Experimental designs that effectively assess refined first person accounts of subjective accounts and that experientially and directly correlate with changes in neural activity will greatly advance and further validate the importance of neurophenomenological approaches for addressing the neural correlates of the consciousness conundrum. While studies that implement methods such as invasive intra-cortical recordings can provide detailed information regarding the neural microcircutry involved in neurofeedback modulation, methods such as fMRI and scalp-EEG are essential for implementing the use of these methods within the general population and non-clinical domains.

Supporting the results and interpretations of the data from our first experiment, new findings from Wokke and colleagues (2016) show that prefrontal theta oscillations directly correlate with first person measures of metacognitive awareness, most likely reflecting the integration of both sensory and cognitive activity in ongoing attention and behavior monitoring. They suggest that these observed theta activations (over AFz) enable connections between the prefrontal cortex and other task related networks that assist in facilitating the top down modulations involved in implementing these processes (Cavanagh & Frank, 2014; Cohen et al., 2009; Driel, Swart, Egner, Ridderinkhof, & Cohen, 2015; Wokke et al., 2016). These findings are particularly relevant in the context of our initial findings (Brandmeyer & Delorme, 2016) showing that advanced meditation practitioners show increased FMθ activity during trials in which they report being more deeply engaged in the meditative state, further validated by additional new findings by Whitmarsh and colleagues (2017) that demonstrated a relationship between metacognitive accuracy and contralateral modulation of somatosensory alpha power. Given that the ongoing monitoring of attention and the continuous subtle attentional adjustments that are necessary to maintain sustained focus during concentration meditation, together these findings further support our claim that meditation practice trains not only sustained attention, but meta-cognitive awareness as well, and that these two cognitive processes may be supported by common underlying neural mechanisms. These findings further validate the claim that meditation training enhances the neural mechanisms underlying metacognitive awareness, and that meditation experience will most likely improve the precision and accuracy of first-person data in the experimental protocols. An outstanding factor relates to the mere act of reporting subjective phenomenon, and the degree to which that may change a given task or state experientially. Ideally, future research will focus on distinguishing both quantitative and qualitative data in a methodologically sound manner (Lutz and Thompson, 2003). Furthermore, it is important to note that while top-down and bottom-up mechanisms and effects can be empirically quantified as independent, the distinct physiological causalities of mental events and neural activity present seemingly insurmountable methodological challenges (Corlier et al., 2016).

8.5 A Unifying theory of Consciousness

To return to the ideas presented in the beginning of this thesis, what do studies investigating neurophenomenology tell us about consciousness, and do these studies bridge not only the explanatory gap of scientifically studying conscious states, but do they provide insight into some of the most fundamental questions we can ask, namely why are we conscious, did life give rise to consciousness having emerged from complex living systems, or is consciousness intrinsic to the universe and something which preceded life? Indirectly and contextually, these studies may provide some interesting insights. An emerging common thread in the scientific study of consciousness is the universal drive to understand why we experience consciousness, and why we are so seemingly unique. It's as if these unanswered questions leave us with an ever present, fundamental anxiety about our direct experience. Could it be that humans and arguably the majority of life have a fundamental drive to alleviate the anxiety of self-awareness, and that the continual push towards understanding these bigger questions is in the hopes of relieving this anxiety, and that theses processes may guide the evolutionary process? Depression, anxiety, neglect, stress and illness all lead towards a decay of structural integrity and health in all animal life. I thus find it not surprising that much of scientific research aims at the understanding and optimization of our physiological, psychological and cognitive functions in order to promote health and happiness.

Together, these ideas stem from my understanding of Panpsychism, and share many commonalities with the theories proposed by Roger Penrose, Stuart Hameroff, David Bohm, Alfred Whitehead, Alan Wallace, Giulio Tononi, Christof Koch, Max Tegmark and many others, all of whom have proposed that any system that contains integrated information can give rise to a conscious experience, and that the more highly integrated a system is, the more holistic the experience of consciousness. This perspective is particularly interesting when taking into account the findings that advanced meditation practitioners exhibit increased fronto-parietal theta and gamma oscillatory amplitude and phase synchrony throughout the brain (Cahn, Delorme, & Polich, 2010; Lutz et al., 2004; Faber et al., 2004; Fell et al., 2010; Baijal & Srinivasan 2010; Lehmann et al., 2001), findings that have been linked to information integration, and that practitioners report that these meditative states and traits serve as a catalyst for the development of sustained states of wellbeing and happiness (Salzberg, 2010; Davidson, 2002; Davidson, 2005; Paulson et al., 2013; Choi et al., 2012; Ricard et al., 2014). Could it be that practices that cultivate mental states associated with this kind neural activity represent more efficiently integrated information and thus higher levels of consciousness?

While the scientific community continuous to struggle with whether consciousness is even definable, or quantifiable, it may be that the answers lie outside the current scientific zeitgeist. According to physicist Richard Hagelin, the current theories of consciousness and human behavior have been modeled entirely on classical concepts derived from nineteenth century physics. Hagelin posits that the recent emergence of more fundamental theoretical frameworks within the discipline of physics have had almost no impact on the field of psychology and neuroscience, possibly due to the fact that very few scientists have been educated beyond the Newtonian era (Hagelin, 1987). The concept of a single, unified reality underlying both mental and physical processes is not new, and was first proposed Spinoza in the 17th century as a response to Descartes, and served as a basis for bringing a sense of unity to the mind-body duality that prevailed over the 16th century. Hagelin argues that the experimental evidence for field effects of consciousness should directly lead us to consider a 'field theoretic framework for consciousness', and that if consciousness exhibits field like behavior, there are 'biological reasons to expect that it may behave like a quantum field' (Hagelin, 1987). These theories share a multitude of commonalities with the majority of the ancient contemplative perspectives, such as Maharishi Vedic Science, which proposes that the mind is 'hierarchically structured in layers from gross to subtle, from excited to de-excited, from localized to unlocalized or field-like, and from diversified to unified. Underlying the subtlest level of mind is the Self—a purely abstract, least excited, completely unified field of consciousness, the dynamic and self-sufficient source of all mental processes' (Maharishi Mahesh Yogi, 1966). Given that it is the fundamental essence of meditation and Yoga practices to experientially inquire into the true nature of mind, it may be that through these methods and techniques of refined observation that one comes closer to the direct experiential understanding of what our experience of consciousness truly signifies.

It is my hope that in this thesis and in the years to come, through the scientific study and understanding of the neural mechanisms underlying meditation, internal thought processes, and the relationship between first person experience and the respective neural correlates, that we will advance our philosophical, medical and scientific understanding of the human mind, mental health and consciousness. These discoveries and the dissemination of these ideas and understandings throughout society will hopefully lead to a better understanding of our expansive capacity for personal, biological, neurological, societal and cultural evolution.

If you want to find the secrets of the universe, think in terms of energy, frequency and vibration."

-Nicholas Tesla

Appendix A: List of Publications and Communications

Publications in International Peer-Reviewed Journals

Brandmeyer, T., and Delorme, A. (2013). Meditation and Neurofeedback. *Frontiers in Psychology* (4)

Brandmeyer, T., and Delorme, A. (2016). Reduced mind wandering in advanced meditation practitioners and associated EEG correlates. *Experimental Brain Research*, p.1-10

Communication in International Conferences

Brandmeyer, T., and Delorme, A. Investigating the Efficacy of Frontal Midline Theta Neurofeedback: A comprehensive approach via EEG, fMRI, MRI and DTI. **Concurrent Talk**, *Towards a Science of Consciousness (TSC) conference 2016*, Tucson, Arizona U.S.A.

Brandmeyer, T., and Delorme, A. Reduced mind wandering in advanced meditation practitioners and associated EEG correlates. **Concurrent Talk**, *Towards a Science of Consciousness (TSC) conference 2015*, Helsinki, Finland.

Brandmeyer, T., and Delorme, A. Reduced mind wandering in advanced meditation practitioners and associated EEG correlates. **Poster Presentation**, *Mind and Life Summer Research Institute 2015* Garrison, New York, U.S.A.

Brandmeyer, T., and Delorme, A. Where Is My Mind: Neural Correlates Of Involuntary Attentional Lapses And Mind Wandering. **Concurrent Talk,** *Towards a Science of Consciousness (TSC) conference 2014*, Tucson, Arizona, U.S.A.

Brandmeyer, T., and Delorme, A. Where Is My Mind: Neural Correlates Of Involuntary Attentional Lapses And Mind Wandering. **Poster Presentation,** *Mind and Life Summer Research Institute 2014*, Garrison, New York, U.S.A.

Appendix B: Publications

frontiers in PSYCHOLOGY

OPINION ARTICLE
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Meditation and neurofeedback

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Dating back as far as 1957, the academic investigation of meditation and the Asian contemplative traditions have fascinated not only the likes of philosophers and religious scholars, but researchers in the fields of neuroscience, psychology, and medicine. While most of the contemplative traditions are comprised of spiritual practices that aim to bring the practitioner closer to self-actualization and enlightenment, from a neuroscientific and clinical perspective, meditation is usually considered a set of diverse and specific methods of distinct attentional engagement (Cahn and Polich, 2009).

Over the last decade, we have witnessed an exponential increase in the interest in meditation research. While this is in part due to improvements in neuroimaging methods, it is also due to the variety of medical practices incorporating meditation into therapeutic protocols. With the general aim of understanding how meditation affects the mind, brain, body and general health, particularly interesting findings in recent research suggest that the mental activity involved in meditation practices may induce brain plasticity (Lutz et al., 2004).

With its increasing popularity, many people in Western societies express an interest and motivation to meditate. However, for many it can often be quite difficult to maintain a disciplined and/or regular practice, for various reasons, ranging from a lack of time to general laziness. It is possible that machine assisted programs such as neurofeedback may help individuals develop their meditation practice more rapidly. Methods such as neurofeedback incorporate real-time feedback of electro-encephalography (EEG) activity to teach self-regulation, and may be potentially used as an aid for meditation.

While Neurofeedback and Biofeedback have been used since the 1960's, previous neuroscientific and clinical research investigating its efficacy has been limited, lacking controlled studies and significant findings (Moriyama et al., 2012). However, a recent overview of the existing body of literature on neurofeedback research has now led the American Academy of Pediatrics to recognize Neurofeedback, as well as working memory training, as one of the most clinically efficacious treatments for children and adolescents with attention and hyperactivity disorders (ADHD) (Dename, 2013). Neurofeedback has been used to treat a wide variety of other disorders such as insomnia, anxiety, depression, epilepsy, brain damage from stroke, addiction, autism, Tourette's syndrome, and more (Tan et al., 2009; Coben et al., 2010; Cortoos et al., 2010; Messerotti Benvenuti et al., 2011; Mihara et al., 2013). As with all therapeutic interventions it is important to note that individuals who are seeking neurofeedback for diagnostics or for clinical and medical purposes seek qualified and licensed practitioners, as adverse effects of inappropriate training have been documented (Hammond and Kirk, 2008).

Interestingly, many of the conditions that benefit from Neurofeedback treatment are consistent with the conditions that improve with regular meditation practice. For example, both ADHD patients and individuals diagnosed with depression benefit from meditation training (Hofmann et al., 2010; Grant et al., 2013) as well as neurofeedback training protocols (Arns et al., 2009; Peeters et al., 2013). In addition, both meditation and neurofeedback are methods of training mental states. Thus, it is plausible that the mental training involved in meditation may be fundamentally no different than other types of training and skill acquisition that can induce plastic changes in the brain (Lazar et al., 2005; Pagnoni and Cekic, 2007).

One hypothesis to explain the similarity between meditation and neurofeedback is that both techniques facilitate and improve concentration and emotion regulation, for which both attentional control and cognitive control are necessary. When one aims to alter attentional control, one must learn to manipulate the amount of attention that is naturally allocated to processing emotional stimuli. Similarly, when an individual is attempting to exercise or gain some form of cognitive control they must alter their expectations and judgments regarding emotional stimuli (Braboszcz et al., 2010; Josipovic, 2010). These core principles are central to both meditation and neurofeedback, with the distinguishing feature being that meditation is self-regulated, and neurofeedback is machine aided. It is worth noting that the alpha and theta frequency bands trained in most cognitive enhancement neurofeedback protocols (Zoefel et al., 2011) share many similarities with the EEG frequency bands that show the most significant change during the early stages of meditation practice (Braboszcz and Delorme, 2011; Cahn et al., 2013).

The integration between meditation and neurofeedback has already happened in popular culture. Numerous neurofeedback companies already provide so-called "enlightenment" programs to the public. The programs developed by these companies, however, are not all based on the scientific study of meditation and/or neurofeedback, and the reliability and accuracy of signal detection in many of the portable devices currently on the market remains questionable. While many of these companies are relying on the intuitions of their founders for various neurofeedback protocols, it is necessary for these programs to adopt a more rigorous scientific approach, such as those developed for clinical patients being treated using neurofeedback (Arns et al., 2009).

Assuming that reliable and reproducible EEG signatures are associated with specific meditation practices, we may expect that training subjects to reproduce these signatures would support and strengthen their meditation practice. Clinical neurofeedback protocols are aiming toward comparing patients' EEG with large EEG data sets from normal subjects in order to produce a neurofeedback algorithm which rewards subjects (patients) whose EEG becomes closer to that of the normal population (Thornton and Carmody, 2009). Similarly, it might be possible to train users to make their EEG brainwaves similar to the brainwaves of an expert practitioner in a given meditation tradition. Note that we do not argue that the task of the user should be only to up-regulate or down-regulate their EEG. Instead, they would perform a meditation practice and the neurofeedback device would act in the periphery, providing users with feedback on how well they are doing. For this to be feasible, there needs to be a clear identification of the EEG neural correlates of specific meditation techniques and traditions. As evidenced in the literature, there are an abundant number of meditation traditions and styles, many which have vastly differing techniques, methods, and practices. As the mental states associated with particular meditations differ, so does the corresponding neurophysiological activity (Cahn and Polich, 2006). Recent research suggests that complex brain activity during meditation may not be adequately described by basic EEG analyses (Travis and Shear, 2010). Thus, more research and the use of more advanced signal processing tools are needed in order to understand the differences in meditative techniques, and to better define a normative population which EEG brainwaves could be used in a neurofeedback protocol.

Another type of neurofeedback program could help detect mind-wandering episodes. In all of the meditation traditions, practitioners often see their attention drifting spontaneously toward self-centered matters. These attentional drifts are termed mind wandering, and have recently been focused on in neuroscientific research (Braboszcz and Delorme, 2011). Interestingly, in this study on mind wandering, EEG changes in the alpha and theta frequency bands have been observed. A neurofeedback device could provide an alarm to users when their mind starts to wander, therefore supporting and improving upon their meditation practice. Although future research should assess the reliability of these measures to detect single mind wandering episodes, such a neurofeedback system might help support users in their meditation.

Most neurofeedback systems provide auditory or visual feedback that fully engage and demand the attention of the subject. For neurofeedback-assisted meditation, the goal would be to provide subtle cues that do not disturb the subjects' meditation. For example, white noise could be made louder as the subject's EEG departs from the EEG of the normative population of meditators. Similarly, the same white noise amplitude could also reflect the likelihood of the subject's mind wandering. As mentioned earlier, the neurofeedback device would not be a substitute to meditation practice, but rather a means to facilitate and support it in its early to middle states of practice.

Over the last century, and ever more so at present, machines have become extensively integrated into a vast range of human activity. The practice of meditation requires sustained attention that is often hard to achieve for novices, as compared to more advanced practitioners (Brefczynski-Lewis et al., 2003). Therefore, an inspiring application of machine-aided learning may be to help offer alternatives for beginners who struggle with maintaining a regular meditation practice. Learning how to meditate faster and more easily may facilitate access to meditation techniques to a wider audience. Still, it may also be beneficial for more experienced meditators who are interested in deepening their meditation practices. Even the Dalai Lama has publicly stated that he would be the first to use this type of technology, and believes that neuroscience will improve Buddhist practices (Mind and Life Institute, 2004).

This type of application also has the potential of reaching the masses as neurofeedback could be introduced to the domain of smartphones and apps (Szu et al., 2013). In fact, some EEG systems are already compatible with portable and smartphone technology, and it will not be long before we start seeing neurofeedback-based programs for smartphones. Community building over social media using cloud based computing could help users support one another and their meditation practices. In addition to supporting meditation practice, neurofeedback applications can help track the progress of users over weeks and years and assess changes that users may not be consciously aware of, thus encouraging users to pursue their practice. Using neurofeedback to learn meditation truly reflects new, cutting edge science, and via real time feedback we may be able to develop a precise ways to rapidly learn and achieve deeper states of meditation.

In conclusion, it is our belief that mobile neurofeedback systems and protocols that are derived and extend upon meditative traditions and practices offer a promising new direction and platform in mobile technology. These technologies would be not only for people who have taken interest in these kinds of practices or people who have already established themselves in a meditative practice, but for people who are looking for new methods to train, improve, and develop attention and emotion regulation. We want to emphasize that neurofeedback should be used as an aid to meditation while people perform their meditation and not as a replacement to meditation, and that while these devices may aid and assist those in their meditative practices, the goal of these practices themselves is ultimately the decrease of reliance on objects and constructs that provide support. This type of research should also integrate neurophenomenological approaches that take into account first-person reports of subjective experience in conjunction with the experimental investigation of brain activity (Braboszcz et al., 2010; Josipovic, 2010). Real time feedback of brain activity as implemented in neurofeedback may help develop new frameworks for the scientific investigation of embodied consciousness and the interactions between mind and body.

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RESEARCH ARTICLE

Reduced mind wandering in experienced meditators and associated EEG correlates

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Abstract One outstanding question in the contemplative science literature relates to the direct impact of meditation experience on the monitoring of internal states and its respective correspondence with neural activity. In particular, to what extent does meditation influence the awareness, duration and frequency of the tendency of the mind to wander. To assess the relation between mind wandering and meditation, we tested 2 groups of meditators, one with a moderate level of experience (non-expert) and those who are well advanced in their practice (expert). We designed a novel paradigm using self-reports of internal mental states based on an experiential sampling probe paradigm presented during ~1 h of seated concentration meditation to gain insight into the dynamic measures of electroencephalography (EEG) during absorption in meditation as compared to reported mind wandering episodes. Our results show that expert meditation practitioners report a greater depth and frequency of sustained meditation, whereas non-expert practitioners report a greater depth and frequency of mind wandering episodes. This is one of the first direct behavioral indices of meditation expertise and its associated impact on the reduced frequency of mind wandering, with corresponding EEG activations showing increased frontal midline theta and somatosensory alpha rhythms during meditation as compared to mind wandering in expert practitioners. Frontal midline theta and somatosensory alpha rhythms are often observed during executive functioning, cognitive control and the active monitoring of sensory information. Our study thus provides additional new evidence to support the hypothesis that the maintenance of both internal and external orientations of attention may be maintained by similar neural mechanisms and that these mechanisms may be modulated by meditation training.

Keywords Mind wandering · Meditation · fm theta · Alpha · Cognitive control · Top-down processing

Introduction

One of the most unique human attributes is our capacity for a vastly complex inner landscape, and our ability to recall, generate and then manifest insight based on experience and predict out into the future. While an elaborate internal dialogue is fundamental to our human experience, this ongoing narrative can surface unknowingly and at inopportune points in time. The later phenomena are commonly referred to as mind wandering or task-unrelated thought and are the experience of thoughts involuntarily drifting to topics unrelated to the task at hand, often occurring under conditions where external demands on our attention are low (Smallwood et al. 2003). In a seminal study by Killingsworth and Gilbert (2010), participants reported being engaged in task-unrelated thought during almost half of their waking hours. While research has demonstrated that mind wandering is essential for creativity and memory consolidation (Baird et al. 2012), under less desirable circumstances excessive

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mind wandering is associated with problems in learning, rumination, anxiety and depression (Poerio et al. 2013; Smallwood et al. 2007). Given the pervasive and complex nature of mind wandering, exploring the neural dynamics underlying mind wandering is a crucial and necessary step toward understanding how the brain produces what William James first referred to as the "stream of consciousness" (James 1890).

Research in functional magnetic resonance imaging (fMRI) has begun to identify the neural networks largely contributing to mind wandering and the generation and maintenance of self-referential thought processes. The default mode network (DMN), comprised of the medial prefrontal cortex (mPFC), posterior cingulate cortex (PCC), superior and inferior frontal gyri, medial and lateral temporal lobes and the posterior portion of the inferior parietal lobule (Gusnard and Raichle 2001; Raichle 2015), shows consistent activations during both probe-caught and self-reported episodes of mind wandering. These episodes typically involve thinking about oneself, others, remembering the past and planning for the future (Buckner et al. 2008). Mind wandering has also been linked to activations in the frontal parietal control network (FPC), a network comprised mainly of the anterior cingulate cortex (ACC), mPFC, amygdala, PCC and the insula, and has been proposed to modulate top-down mechanisms involved in sustaining both endogenous and exogenous forms of attention allocation (Spreng et al. 2013). Spreng et al. (2013) suggest that goal-directed cognition is facilitated by the FPC, which functions as a gatekeeping system by moderating the dynamic balance between activations in the DMN and the dorsal attention network (DAN). It might also facilitate alternating or competing goal representations while maintaining directed attention to a given external task (i.e., driving, running; Spreng 2012). Concurrent activations in both the DMN and core regions of the executive functioning network (dorsolateral mPFC, ACC), networks that were traditionally considered independent, anti-correlated and thought to compete for cognitive resources, were also shown to co-activate during mind wandering episodes, and increasingly so when subjects reported being unaware of their mind wandering (Christoff et al. 2009). Interestingly, emphasis on the flexible monitoring of ongoing experience during meditation is thought to be responsible for the increased functional connectivity in DMN activations observed in expert meditation practitioners trained in internally guided forms of sustained attention (Tang et al. 2015; Jang et al. 2011). Taken together, these findings support the notion that both internally and externally directed forms of cognitive activity may recruit the DMN, as well as some overlapping regions of the executive networks.

An intriguing finding emerging from the field of contemplative neuroscience involves the mediating role of contemplative and meditative practices on the neural mechanisms underlying top-down regulation of sustained attention and sensory perception. An electroencephalography (EEG) study by Braboszcz and Delorme (2011) showed enhanced cortical processing of sensory stimuli during a sustained breath awareness task when compared to periods of time in which subjects reported mind wandering. Known as the perceptual decoupling hypothesis, the processing of sensory information during periods of mind wandering is more superficial (Schooler et al. 2011). Mrazek et al. (2013) found that after two weeks of mindfulness meditation training, participants who were initially most prone to distraction showed improved verbal GRE scores after meditation training in addition to enhanced working memory capacity as measured by the OSPAN working memory task. These changes were directly mediated by reduced mind wandering as measured by experience sampling using both probe-caught and self-reported mind wandering episodes during both the GRE and OSPAN. In another study by Mrazek et al. (2012), eight minutes of mindful breathing attenuated indirect performance markers of mind wandering during a sustained attention task. In a set of studies by Zanesco et al. (2016) exploring the effects of intense meditation training on mind wandering, two separate groups of participants who took part in either a one month insight meditation retreat, or a three month shamatha meditation retreat, showed a reduced tendency of the mind to wander as measured by reduced mindless reading and reduced probe-caught mind wandering measured during a reading task requiring ongoing error monitoring.

Arguably the cornerstones of most contemplative practices include the training and development of sustained attention (Slagter et al. 2007), the flexible monitoring of sensory experience (Kerr et al. 2011; Tang et al. 2015) and the cultivation of metacognitive awareness via active monitoring of mental states (Baird et al. 2014). Taken together, these faculties may facilitate increased efficiency in the distribution of our limited cognitive resources (Global workspace theory; Baars 2005). Increased functional connectivity in networks associated with both attention and executive functioning (Hasenkamp and Barsalou 2012; Teper and Inzlicht 2013) has been observed in advanced meditation practitioners, in addition to the aforementioned findings in the DMN (Jang et al. 2011). Given the large body of literature showing reduced DMN activations in advanced practitioners and that meditation leads to reduced DMN processing beyond that observed during other types of cognitive tasks (Garrison et al. 2015), together these findings could suggest that increased functional connectivity may reduce BOLD activity, reflecting an efficient use of cognitive resources. Contrary to these findings, a recent study by Berkovich-Ohana et al. (2016) found reductions in functional connectivity in experienced meditators; therefore, more research is needed to clarify the neurophysiological implications of functional connectivity in meditation practice and beyond.

In a study using magnetoencephalographic (MEG) recording of the SI finger representation, Kerr et al. (2011) found that experienced meditators showed an enhanced alpha power modulation in response to a cue, potentially reflecting an enhanced filtering of inputs to primary sensory cortex. They also found that experienced meditators demonstrated modified alpha rhythm properties and an increase in non-localized tonic alpha power when compared to controls. These findings can most likely be attributed to the emphasis on somatic attention training in mindfulness meditation techniques in which individuals train to develop metacognition, a process in which one directs their attention, moment-by-moment, to an overall somatosensory awareness of physical sensations, feelings and thoughts (Segal et al. 2004; Cahn and Polich 2006). Whitmarsh et al. (2014) investigated participants metacognitive ability to report on their attentional focus and found that contralateral somatosensory alpha depression correlated with higher reported attentional focus on either their left or right hand, respectively. Baird et al. (2014) found that a 2-week meditation program leads to significantly enhanced metacognitive ability for memory, but not for perceptual decisions, suggesting that while meditation training can enhance certain elements of introspective acuity, such improvements may not translate equally to all cognitive domains. Enhanced body awareness was also found to be associated with greater subjective emotional experience and awareness of the heart during exposure to emotionally provocative stimuli in vipassana meditators, when compared to expert dancers, and controls (Sze et al. 2010). Given that top-down attentional modulations of cortical excitability have been repeatedly shown to result in better discrimination and performance accuracy, the aforementioned findings provide support for both the enhancement of metacognitive accuracy via the direct monitoring of current mental states resulting from long-term meditation practice, and for potential changes in the supporting neural structures underlying sustained attention processes.

One outstanding question in the contemplative science literature relates to the direct impact of meditation experience on the monitoring of mind wandering and the degree to which practice influences the metacognitive awareness, duration and frequency of mind wandering events. In order to extend our scientific understanding of these temporally fluctuating mental states and phenomena in experimental settings, and given that subjects are generally unaware of mind wandering at the moment it occurs, the direct measurement challenge this poses for identifying the underlying mechanisms involved in attentional lapses requires nuanced neuroimaging methodology. Thus, we designed a novel paradigm based on experience-sampling probe presentations to gain insight into the dynamic measures of EEG by comparing the degree (subjects responded on a scale from 0 to 3) of self-reported absorption experienced during meditation with the self-reported absorption experienced during mind wandering. To assess the relation between mind wandering and meditation, we tested 2 groups of meditators, one with a moderate level of experience and one with an advanced practice level. The central question in this investigation is to test whether the level of meditation proficiency enhances the capacity for sustained attention, the awareness of and accuracy of self-report, and the metacognitive labeling of mental states. Our goal was also to contrast the neural dynamics of mind wandering and meditation, as well as an overall correlation between the EEG data and the first person behavioral data in this context.

Methods and materials

Participants

The study was conducted at the Meditation Research Institute (MRI) in Rishikesh, India. Twenty-five meditators from the Himalayan Yoga tradition participated in this study and were assigned to one of two groups based on experience and hours of daily practice. After data collection, one participant reported that they did not fully understand the task instructions and was excluded from the analyses; therefore, twenty-four participants were included in the analyses. Individuals who had engaged in a daily meditation practice for a minimum of 2 h daily for 1 year or longer were considered expert practitioners (3 females; mean hours weekly = 14.8, SD = 1.6 h; mean age = 39.3, SD = 12.0). Participants who were trained and familiar with the techniques, but who reported irregular practice (10 females; 3.2 mean weekly hours with SD of 3.1 h; mean age of 45.0 with SD of 14.8), were considered non-expert practitioners. All participants provided written consent to participate in the study and completed an extensive list of questions regarding their meditation background. Participants stated that they were not taking any medications that could potentially affect their concentration. The study received ethical approval from both the ethics committee of the Meditation Research Institute in India, and from the *Comite de Protection des Personnes* in France. Participants were all volunteers and were not compensated.

Experimental paradigm and procedure

All participants were asked to meditate continuously throughout the experiment in their usual seated meditation position (either seated on the floor, or in a chair).

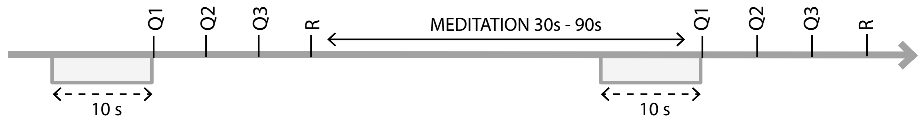

Fig. 1 Timeline of experimental design. Pseudorandom probes (randomly interspaced between 30 and 90 s) prompted subjects to respond via key press by subjectively evaluating the depth of their experience on a scale from 0 to 3 to three questions: *Q1* for "Please rate the depth of your meditation"; *Q2* for "Please rate the depth of your mind wandering"; *Q3* for "Please rate how tired you are." The letter *R* on the timeline corresponds to the instruction "You may now resume your meditation"

Meditators were all practitioners of the Himalayan Yoga tradition. Once subjects were comfortably seated in their meditative posture, they were instructed to begin their meditation. All practitioners began with an initial body scan as they relaxed into their seated posture and then started to mentally recite their mantra. Mantras are traditionally a word or sentence assigned to them by their meditation teacher. When deeper levels of meditation or stillness are obtained, mantra repetitions gradually cease. Mantras are derived from Sanskrit root words and syllables, whose resonance is thought to induce stability of the mind without the need for an overly intense focus.

Experience-sampling probes were presented at random intervals ranging from 30 to 90 s throughout the duration of the experiment. Probes, in the form of pre-recorded vocalized questions, were presented on two freestanding speakers and were reported as clearly audible by all subjects. Each experience-sampling probe series consisted of three questions, which were presented in the same order throughout the experiment and are described in detail below. Subjects responded on a small customized numeric USB keypad resting on their right thigh, to enable their right hand to comfortably rest without having to move or open their eyes. The time range of the experiment lasted from 45 min to 1 h 30 min, as some subjects were willing and able to sit comfortably for longer periods of time. The minimum number of probes that participants received was 30. The entire experiment was programmed and automated using the MATLAB psychophysics toolbox. All participants completed a 5-min training block prior to performing the experiment.

Experience-sampling probes consisted of three questions that followed sequentially (Fig. 1); the first question was Q1: "Please rate the depth of your meditation," for which participants evaluated the subjective depth of their "meditative state" for the moments immediately preceding the first probe, on a scale from 0 (not meditating at all) to 3 (deep meditative state) by pressing the corresponding key on the keypad. After their response was registered, the second question Q2: "Please rate the depth of your mind wandering" automatically followed. Participants evaluated the subjective depth of their "*mind wandering*" for the period of time which immediately preceded the first probe, on a scale from 0 (not mind wandering at all) to 3 (immersed in their thoughts). The last question was Q3: "Please rate how tired you are," where participants were asked to rate the subjective depth of their drowsiness at the time of the first question, from 0 (not drowsy at all) to 3 (very drowsy). All responses pertained to the evaluations of the same time period immediately preceding the first probe. Participants were then instructed to resume their meditation with the prompt: "You may now resume your meditation."

Data acquisition

We collected data using a 64-channel Biosemi system and a Biosemi 10–20 head cap montage at 2048 Hz sampling rate. All electrodes were kept within an offset of 15 using the Biosemi ActiView data acquisition system for measuring impedance. Respiration, heart rate (ECG/HRV) and galvanic skin response (GSR) were also recorded, but results from these data will not be reported here.

Data processing was done using MATLAB (The MathWorks, Inc.) and EEGLAB software (Delorme and Makeig 2004). The raw EEG data were average referenced and down-sampled from 2048 to 256 Hz. A high-pass filter at 2 Hz using a infinite impulse response filter (IIR; transition bandwidth of 0.7 Hz and order of 6) was applied, and the data were then average referenced again. The high-pass filter was necessary to obtain high-quality ICA decompositions on some subjects (see below) and, even though it was not necessary for all subjects, we opted to use the same high-pass filter settings for all subjects to ensure that all data were processed uniformly. Data were then segmented into 10 s-epochs, ranging from −10.05 to −0.05 s prior to the onset of question Q1 in the experience-sampling probe series. Bad electrodes (0–20 per subject, average of 6 per subject) and bad epochs containing paroxysmal activity were manually removed. Extended Infomax Independent Component Analysis (ICA) was then used to identify ocular and muscle artifacts (Delorme et al. 2007). ICA components for eye blink, lateral eye movements and temporal muscle noise were identified and subtracted from the data by the visual inspection of both the component scalp topographies and power spectrum distributions. Between 1 and 5 artifactual components were removed for each subject. After artifact rejection, between 21 and 64 clean data epochs (mean of 38.1; SD of 12.6) were included in subsequent analyses for each subject.

EEG time frequency analysis and statistics

We applied a Welch-like analysis on the 10-s-long epochs (Welch 1967). The difference with the Welch method is in its implementation of wavelets instead of the fast Fourier transform (FFT). We used a Morlet wavelet decomposition with 200 linearly spaced time windows and a series of 100 log-spaced frequencies that range from 1 to 128 Hz. The wavelet used to measure the amount of data in each successive, and overlapping time window has a 3-cycle wavelet at the lowest frequency. The number of cycles in the wavelets used for higher frequencies increases linearly, reaching 60 cycles at its highest frequency of 128 Hz.

Parametric statistics for behavioral results were performed in Excel, Statistica and MATLAB using paired t test, unpaired t test with unpooled variance estimates, and linear regression. For EEG data, statistics were conducted on topographic and time–frequency maps using two-tailed paired or unpaired statistics. For the EEG data, correction for multiple comparisons was performed using the cluster method developed by Maris and Oostenveld (2007), which is based on a nonparametric Monte Carlo permutation method. Channel topographies for this clustering method were established by setting the number of channel neighbors to 4.5 (Maris and Oostenveld 2007). We also used false discovery rate (Benjamini and Yekutieli 2001) to correct for multiple comparisons and obtained similar results as compared to the cluster method.

Table 1 Average response for non-expert (NE) and expert (E) meditators on the 3-question experiential probes series pertaining to meditation (Q1: Med), mind wandering (Q2: mind wandering) and drowsiness (Q3)

	Med	MW	Sleep
Non-expert meditators			
NE1	2.64	1.27	1.09
NE2	0.82	1.55	0.08
NE3	1.6	1.56	0.48
NE4	1.14	2	0.95
NE5	2.05	0.46	0.31
NE6	0.6	1.58	1.34
NE7	1.16	1.88	0.06
NE8	1.34	1.66	0.03
NE9	1.6	2.56	1.88
NE10	0.76	1.12	0.53
NE11	1.74	1.62	0.06
NE12	1.27	1.85	1.95
Mean	1.39	1.59	0.73
Expert meditators			
E1	1.31	1.33	0.7
E2	1.2	1.09	0.7
E3	1.61	1.21	0.68
E4	1.16	0.47	0.06
E5	1.45	0.86	0.57
E6	1.43	1.17	0.07
E7	2.42	0.88	0.3
E8	2.5	1.46	1.62
E9	2.53	0.52	0.08
E10	1.95	1.4	0.28
E11	2.54	1.17	1
E12	2.07	2.14	2.21
Mean	1.85	1.14	0.69

Results

Behavioral data

Expert practitioners reported a significantly lower depth of mind wandering than non-expert practitioners (mean 1.14 vs. 1.59; with parametric unpaired two-tailed t test with correction for non-homogeneous variance $p = 0.03$; with permutation statistics and 20,000 permutations $p = 0.03$). Expert practitioners also reported a greater depth of meditation than non-experts, although this effect failed to reach significance (mean 1.85 vs. 1.39; degree of freedom (*df*) of 11; with parametric statistics $p = 0.06$; with permutation statistics $p = 0.06$). When taking the rating difference between the two questions (Q1 minus Q2), the difference between expert and non-expert practitioners was even larger (mean −0.20 vs. 0.71; with parametric statistics $p = 0.0084$; with permutation statistics $p = 0.0088$). There was no difference in terms of alertness between expert and non-expert participants, and all participants were relatively alert as reflected by the low tiredness ratings (mean 0.69 vs. 0.73; ns with both parametric and permutation statistics). No significant correlations were observed between meditation and mind wandering ($r^2 = 0.05$; ns) or between meditation depth and drowsiness ($r^2 = 0.02$; ns) when all participants were pooled together. When considering the two groups of participants, such correlation was again low and not significant. However, a strong positive correlation was observed between mind wandering and drowsiness across all participants ($r^2 = 0.31$; $p = 0.004$), with positive correlations observed for both groups of subjects, and reaching significance for expert practitioners ($r^2 = 0.66$; $p = 0.0013$) but not for non-expert practitioners ($r^2 = 0.2$; ns). Average subject responses are summarized in Table 1.

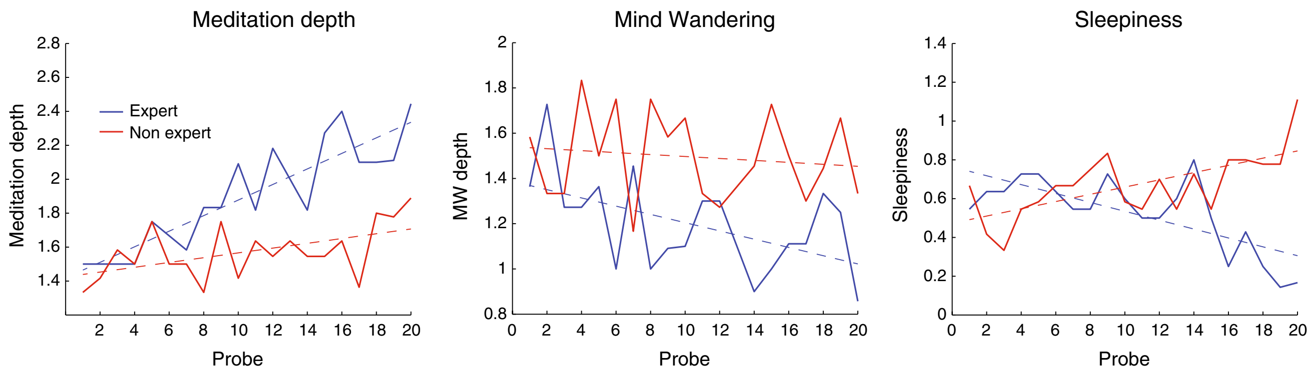

Fig. 2 Evolution of the responses to experiential probes throughout the experiment for the three questions pertaining to meditation depth, mind wandering and sleepiness. Only the first 20 probes for each subject are shown. *Thick lines* indicate mean response on each probe for the two groups of participants. *Dashed lines* indicate linear regressions. Significative results are reported in the text

To test whether responses to probes changed over time, we compared the behavioral responses for the first 20 probes, comprising at least 75% of the subjects (probes were delivered at random intervals; thus, subjects received a varying number of probes—3 subjects in each group had less than 20 probes). As shown in Fig. 2, although both groups start at approximately the same meditation depth, the group of expert practitioners showed a highly significant increase from 0.034 to 0.058 points in the depth of their meditation over time, $p = 0.0000002$; $r^2 = 0.8$ (the ranges provided here indicate a 95% confidence (CI) interval, with all statistics using parametric methods), as well as a significant increase for non-expert practitioners, $p = 0.02$; $r^2 = 0.27$ (increase from 0.003 to 0.026 points in meditation depth per probe). No significant difference was observed in the intercept between the two groups, with a 95% confidence interval for a non-overlapping slope indicating a significant difference between the two groups. A regression analysis revealed a significant reduction over time for the mind wandering scale for the expert practitioners ($p = 0.02$; $r^2 = 0.27$ for experts, and $p =$ ns; $r^2 = 0.02$ for non-experts). The decrease in mind wandering for experts was significantly negative, with a slope CI of −0.033 to −0.003. The intercept between the two groups did not differ significantly. Interestingly, our sleep-scale measures indicate that the non-expert group experienced increased drowsiness compared to the expert group at the onset of the experiment (CI of 0.62–0.86 at the first probe for the expert group and 0.37–0.61 for non-expert group), suggesting that meditation experience may potentially affect overall subjective alertness level. Additionally, the expert group reported a significantly reduced depth of drowsiness as the experiment progressed, while the non-expert group report significantly increasing drowsiness (slope CI of −0.034 to −0.012 for experts and 0.008–0.029 for non-experts). Both regressions were highly significant (experts $p = 0.0004$; $r^2 = 0.51$ vs. non-experts $p = 0.002$; $r^2 = 0.43$).

While significant behavioral differences were observed between experts and non-experts when considering mind wandering, we observed large inter-subject variations. The relatively large variance across participants was most likely due the subjective nature of the task. Participants were likely to have rated the questions differently—with some participants being biased toward providing high ratings, as compared to others being biased toward providing low ratings. This is consistent with the fact that we observed larger differences between expert and non-expert practitioners when we considered the normalized individual ratings for both the meditation and mind wandering responses, than when we considered absolute ratings. Calculating the differences between the ratings of these two questions effectively minimized the absolute response bias participants may have had. Since a comparison of ratings across participants is subject to a large amount of noise, we adopted the strategy of splitting trials in two categories: trials for which ratings on the meditation scale were larger (considered meditation trials) than mind wandering and vice versa (mind wandering trials). Trials when the two ratings for the two conditions were equal were ignored. Two subjects were excluded from these analyses because they reported no behavioral trials for one of the two conditions.

Our behavioral analyses found that expert practitioners reported significantly more meditation trials as compared to mind wandering trials [mean of 75.4 trials for Med; mean of 24.6 trials for mind wandering; standard error (SE) of 4.4 in both cases, $p = 0.00014$], while non-expert practitioners showed no such effect (mean of 42.7 trials for Med; mean of 57.3 trials for mind wandering; SE of 6.2, ns) as shown in Fig. 3. Group-level statistics showed that

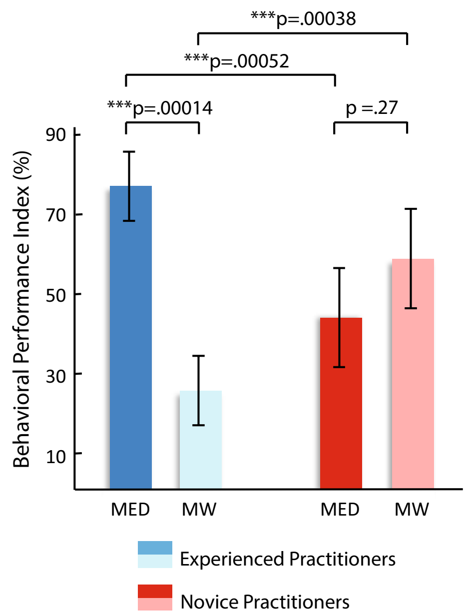

Fig. 3 Expert practitioners reported a greater number of probed trials in which they were actively engaged in their meditation as compared to mind wandering. They also reported a greater number of probed trials in which they were actively engaged in their meditation than non-expert practitioners. *Error bars* indicate 95% confidence intervals which was calculated by multiplying the standard error by 1.96

non-expert practitioners reported a significantly greater number of mind wandering trials as compared to expert practitioners (difference of 32.7; $p = 0.00038$) and that expert practitioners reported a significantly greater number of meditation trials as compared to non-expert meditators (difference of 32.7; $p = 0.00052$).

EEG activity time-locked to experience-sampling probes

Event-related spectral perturbation (ERSP) of the EEG signal was assessed during the 10-s immediately preceding probe onset (see "Methods and materials" section). Expert practitioners showed significantly increased modulation of theta activity (4–7 Hz) across the frontal cortex ($p < 0.02$ after correction for multiple comparisons), as well as alpha activity (9–11 Hz) primarily concentrated over the somatosensory cortex ($p < 0.02$), during meditation trials as compared to mind wandering trials. When the same analysis was conducted on the non-expert meditation group, no significant differences were observed (see discussion). No interaction was observed between trial type and meditation expertise.

For each expert subject, we averaged the theta and alpha power for the electrodes which showed significant differences in both frequency bands (Fig. 4). We observed a positive correlation between theta difference between meditation and mind wandering state and alpha power difference between meditation and mind wandering state ($r^2 = 0.42$; $p = 0.02$), indicating that subject that had a larger theta difference between conditions also had a larger alpha difference. We did not observe correlations between behavioral responses (responses averages for expert subjects from Q1 to Q3 in Table 1) and theta or alpha power differences.

Discussion

Our results provide some of the first evidence that meditation expertise is associated with an attenuated frequency

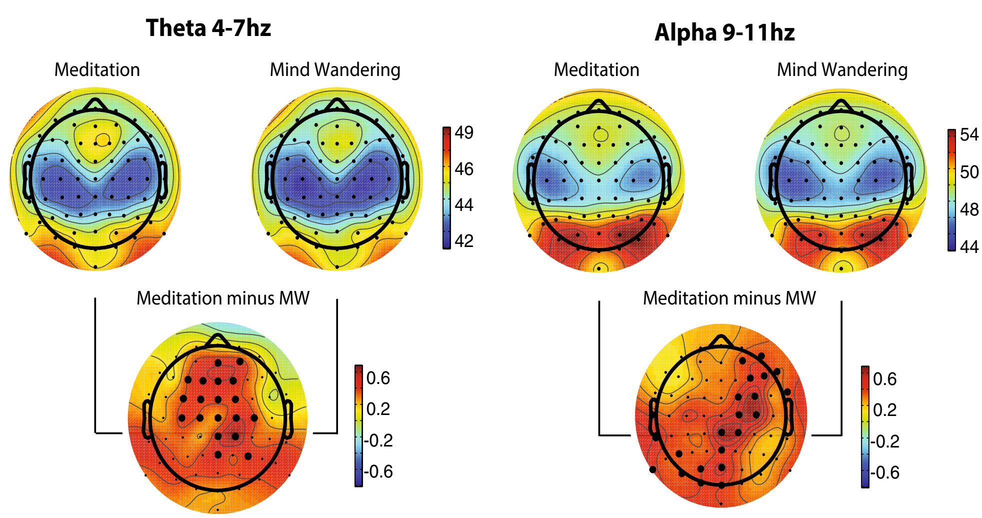

Fig. 4 Event-related spectral perturbation (ERSP) plots, and differential plots of significance in theta (4–7 Hz) and alpha (9–11 Hz) band activity for expert meditation practitioners. Power scale is expressed in μV^2/Hz. Black dots on the difference plots indicate electrodes significant at $p < 0.02$ after cluster correction for multiple comparisons

of mind wandering. We observed that meditation expertise was associated with a significantly greater depth of meditative absorption and a significantly reduced number of mind wandering episodes meausred throughout our experience-sampling paradigm. These findings suggest that meditation training reduces the susceptibility of the mind to wander, subsequently leading to longer periods of meditative absorption (discussed below). Our findings provide supporting evidence that increased theta activity over mid-frontal theta regions and alpha activity primarily focused over the somatosensory cortex are markers of sustained and internally directed attentional states of awareness cultivated via long-term meditation practice. Additionally, the modulations seen in mid-frontal theta and somatosensory alpha, both traditionally markers of various types of executive functions, add to an expanding body of literature suggesting that meditation training may modulate some of the neural mechanisms involved in cognitive control and attention (Hölzel et al. 2011; Mrazek et al. 2013; Slagter et al. 2007). Given that our limited sample size ($n = 24$) was made of individuals who practiced exclusively in the Himalayan meditation tradition, further studies are necessary to validate our findings in other meditation traditions.

Our EEG findings indicate that the mid-frontal theta and somatosensory alpha rhythms, often observed during executive functioning tasks and cognitive control (Cavanagh and Shackman 2015; Cavanagh and Frank 2014; Enriquez-Geppert et al. 2014; Bollimunta et al. 2011), can also be seen during internally guided states of focus such as meditation and are consistent with previous research (Aftanas and Golocheikine 2001; Kerr et al. 2013). It may also suggest a functional relationship between the sources contributing to our observed mid-frontal theta activity and the broader frontoparietal control network involved in maintaining top-down representations of goal states, learning and directed attention (deBettencourt et al. 2015; Spreng 2012; Cavanagh and Frank 2014). The role of theta in meditation practice and the cultivation of top-down control via the enhancement of monitoring and possibly enhanced conflict detection falls in line with the established literature regarding its specific role in learning (Swick and Turken 2002; Haegens et al. 2010). Cavanagh and Frank (2014) have suggested that cortical theta-band oscillations may serve as a candidate mechanism by which neurons communicate top-down control over long-range and broad networks. Mid-frontal theta has been proposed to function as a temporal template for organizing mid-frontal neuronal processes, and theta-band phase dynamics may entrain disparate neural systems when cognitive control is needed (Cavanagh and Frank 2014). This is supported by findings suggesting that cortical and subcortical areas are interconnected via the cingulate cortex (Morecraft and Tanji 2009; Bollimunta et al. 2009). Our study thus provides new evidence to support the claims posited by Spreng (2012) that the maintenance of both internal and external orientations of focus may be maintained by similar neural mechanisms. Our findings suggest that meditation training may target the neural substrates underlying these oscillations.

The observed increase in alpha activity in our expert meditation group supports it putative role in the processing and integration of somatosensory information (Kerr et al. 2013; Whitmarsh et al. 2014), and cognitive entrainment. Somatosensory alpha modulation has been established in the facilitation of working memory performance, in addition to mindfulness meditation practitioners showing an enhanced ability to modulate alpha power in sensory neocortex in response to a cue (Kerr et al. 2013). Kerr et al. (2013) suggest that mindfulness meditation enhances top-down modulation of alpha by facilitating precise alterations in timing and efficacy of the somatosensory cortex thalamocortical inputs. Thus, our findings of enhanced alpha activity support these respective findings and are consistent with the hypothesis that cortical mechanisms underlying somatosensory perception may be modulated by meditation training. Furthermore, our findings provide further support for theories that an enhanced integration of sensory information and attention can be learned and modulated via top-down mechanisms.

Our implementation of a probe-caught mind wandering paradigm was based on previous findings which suggest that this method is thought to reflect the actual frequency of mind wandering episodes, whereas mind wandering that is self-reported may reflect an individual's metacognitive awareness of mind wandering (Smallwood and Schooler 2006). While meditation practice may increase the number of self-caught mind wandering episodes over time by enhancing metacognitive awareness of internal experience, it may also be due to a reduced number of lapses of task-related attention following extensive training, limiting the opportunities for practitioners to subsequently identify and report mind wandering episodes. Thus, variations in reports from both self- and probe-caught mind wandering paradigms should be mutually considered in future studies. While our research findings do suggest that overtime meditation practice may fundamentally reduce the frequency of spontaneous thought, this may occur alongside the ability to actively identify and disengage from mind wandering and subsequently reorient attention. It may also be the case that meditation practice facilitates the unification of various attentional mechanisms so as to moderate mind wandering. Future avenues of research on mind wandering and meditation training should focus on disentangling whether meditation increases the metacognitive awareness of mind wandering and the subsequent reorientation of attention, if meditation enhances a fundamental capacity of allocating attentional resources, or if meditation facilitates an overall reduction in the occurrence of mind wandering events as our findings suggest.

It remains possible that what distinguishes experts from novices is not necessarily their attentional capacity for internal focus per se, but rather their metacognitive capacity to accurately label mental states (Baird et al. 2014). It is also important to note that due to the nature of our experimental paradigm in which participants were being auditorily probed about every 3 min, exit interviews indicated that the majority of participants were unable to experience particularly "deep" meditative states. As indicated in our behavioral data, both groups experienced a progressive increase in the depth of their meditation over time, suggesting that both groups progressed in their ability to engage in their meditation practice and perform the task simultaneously. Given that meditative experience enhances individuals' ability to monitor internal states, it would follow that expert meditators would also be better at labeling these states. Thus, we cannot rule out the possibility that our novice meditators were engaged in focused meditative practices in a way that would be similar to experts and that the differences in EEG we observed were due to a decreased capacity of novices to accurately label mental states. Our corresponding EEG and behavioral findings in expert practitioners may therefore provide supporting evidence for an enhanced metacognitive accuracy in reporting as a result of long-term meditation practice.

Cognitive control is one of the most essential sets of cognitive functions for our interactions with the external world, with individual differences in these cognitive functions predicting success across academic and professional domains (Hirsh and Inzlicht 2010). Research is beginning to confirm that impaired cognitive control in the hallmark of clinical disorders such as ADHD, obsessive compulsive disorder and schizophrenia (Kaser et al. 2013; Yordanova et al. 2013; Mazaheri et al. 2014). Our findings suggest that contemplative practices and techniques may be useful in treating an increasingly wide array of medical and clinical disorders through training and exercising the neural circuitry underlying the top-down regulation of executive functions, somatosensory processing and metacognition. Furthermore, they provide support for the development of cognitive protocols and brain computer interfaces that aim to modulate these neural networks and their underlying cortical and subcortical structures.

Our behavioral results are one of the first to show that an attenuated frequency of mind wandering can be considered a direct marker of meditation expertise. Furthermore, the corresponding behavioral and EEG findings in our expert practitioner group provide evidence for enhanced metacognitive accuracy in reporting as a result of long-term meditation practice. Finally, the increased mid-frontal theta and alpha rhythms observed during meditative absorption provide direct evidence to support the hypothesis that the maintenance of both internal and external orientations of focus may be maintained by similar neural mechanisms.

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Résumé

Le travail présenté dans cette thèse vise à nous amener à une meilleure compréhension des relations fines entre ce que nous expérimentons phénoménologiquement sous la forme d'états mentaux, et les effets sous-jacents et potentiellement causaux sur l'activité neuronale. Afin d'étendre notre compréhension scientifique de l'expérience consciente, nous avons d'abord mis l'accent sur un phénomène appelé la pensée spontanée ou vagabondage de l'esprit. Notre paysage intérieur est un aspect essentiel et complexe de notre expérience humaine, avec des recherches suggérant que les gens sont engagés dans une forme de dialogue intérieur sans rapport avec leur environnement immédiat 50% de leur temps de veille. De plus, le vagabondage de l'esprit a constamment été associé à un affect négatif, même lorsque son contenu est positif. Il est alors intéressant de noter que les fondements de la plupart des pratiques méditatives et contemplatives sont la formation de l'observation flexible et continue des états mentaux et de l'expérience sensorielle, le développement d'une attention soutenue et la culture de la conscience métacognitive. Étant donné que nous ne sommes généralement pas au courant de la fluctuation temporelle de ces états mentaux dans le temps (vagabondage de l'esprit), les méditants sont des sujets idéaux pour obtenir de manière précise des rapports phénoménologiques et des descriptions des états à la première personne. Ainsi, nous avons conçu un paradigme nouveau basé sur présentation de sondage d'expérience aux méditants afin de mieux comprendre les mesures dynamiques de l'EEG (Electroencéphalographie) pendant la méditation. Nos résultats suggèrent que la pratique experte de méditation est associée à une fréquence atténuée de la pensée spontanée et que l'entraînement à la méditation réduit par la suite la susceptibilité de l'esprit à errer, menant à des périodes d'absorption méditative rapportées comme étant plus longues. Les augmentations de l'activité thêta (4-7 Hz) sur les régions thêta frontales médianes ainsi que l'activité alpha (9-12 Hz), principalement focalisée sur le cortex somatosensoriel, semblent être des marqueurs d'états méditatifs soutenus par rapport au vagabondage mental. Sur la base de la robustesse de l'activité thêta de la ligne médiane frontale chez les méditants avancés, ainsi qu'une multitude de résultats démontrant que l'activité thêta frontale serait le pilier du contrôle cognitif via l'intégration et l'échange d'informations de longue portée, nous avons développé un protocole de neurofeedback méthodologiquement nouveau et exhaustif dans le but d'entraîner l'activité thêta (3.5-6.5 Hz) de la ligne médiane frontale Fz, en donnant comme instruction à nos sujets de s'engager dans des techniques de respiration et de relaxation similaires à la méditation. Nous avons constaté que les sujets qui ont reçu le vrai neurofeedback ont été capables de moduler significativement leur activité thêta Fz (3-7 Hz) à travers huit séances de neurofeedback par rapport aux sujets contrôles qui ont reçu un feedback apparié. Nous avons également observé des modulations significatives dans les bandes de fréquences alpha (9-11 Hz) et bêta (13-20 Hz) chez les sujets qui ont reçu l'entraînement réel de neurofeedback, ainsi que des améliorations sur plusieurs mesures des fonctions exécutives. Nos résultats réduisent davantage l'écart explicatif en reliant caractéristique neurophysiologique et données à la nature phénoménologique de notre expérience.